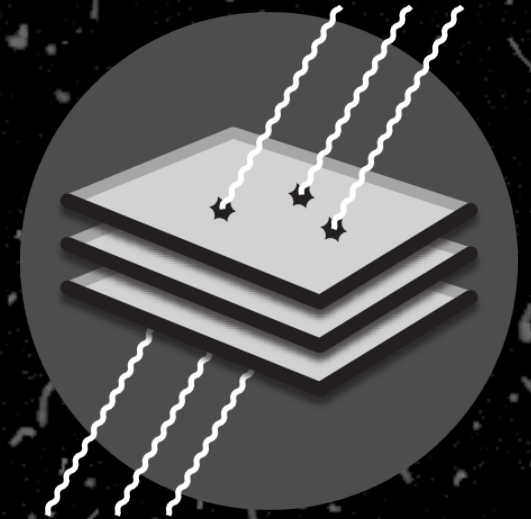


DAMIC : a novel use of CCDs for dark matter searches

**Ben Kilminster
U.Zürich**

**PATRAS
July 3, 2014**



Naturalness of Dark Matter Mass scale

1. “Wimp miracle” scale : $M_{\text{DM}} \sim 100 \text{ GeV}$

- SUSY weak cross-sections provide DM density relic Ω_{DM}

2. “Baryon-DM coincidence” scale : $M_{\text{DM}} \sim 5 \text{ GeV}$

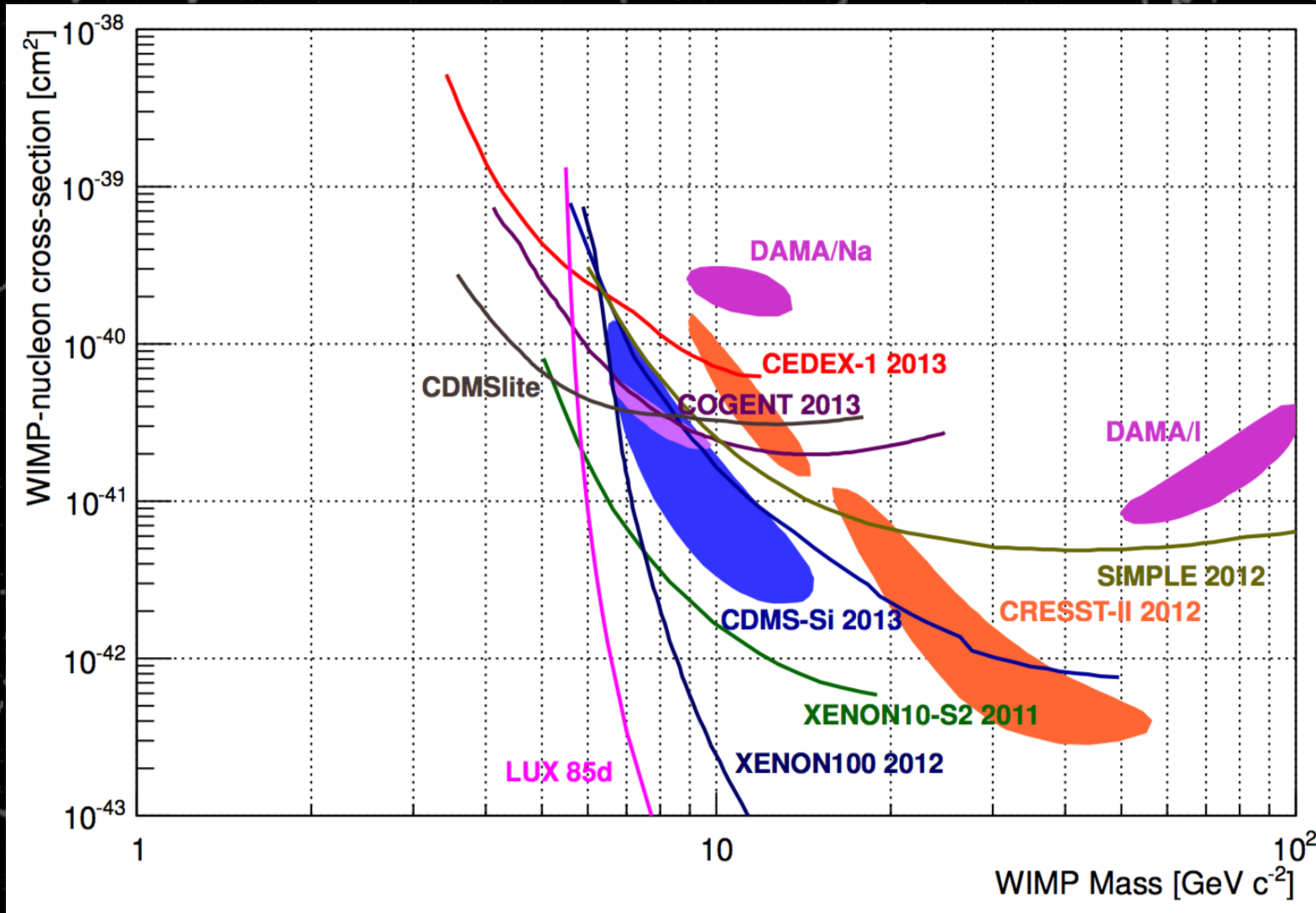
- $\rho_{\text{DM}} \approx 5 \rho_{\text{B}}$
 - Why is ρ_{DM} similar to ρ_{B} ?
 - Each is set by independent processes
 - ρ_{B} is set by CP violating phase
 - ρ_{DM} is set by ie, SUSY mass hierarchy of LSP

- Assume that at start of universe : $N_{\text{DM}} = N_{\text{M}}$
- Lepton-baryon asymmetry transferred to DM : $N_{\ell} - N_{\bar{\ell}} = N_{\text{DM}} - N_{\bar{\text{DM}}}$
- If $\rho_{\text{DM}} \approx 5 \rho_{\text{B}}$
→ $M_{\text{DM}} = 5 * M_{\text{proton}}$

Asymmetric DM
hep-ph/1111.0293

Or Intuitively : same number of DM and M particles, but 5 times density
→ DM is 5 times more massive than M

Experimental hints of DM ...

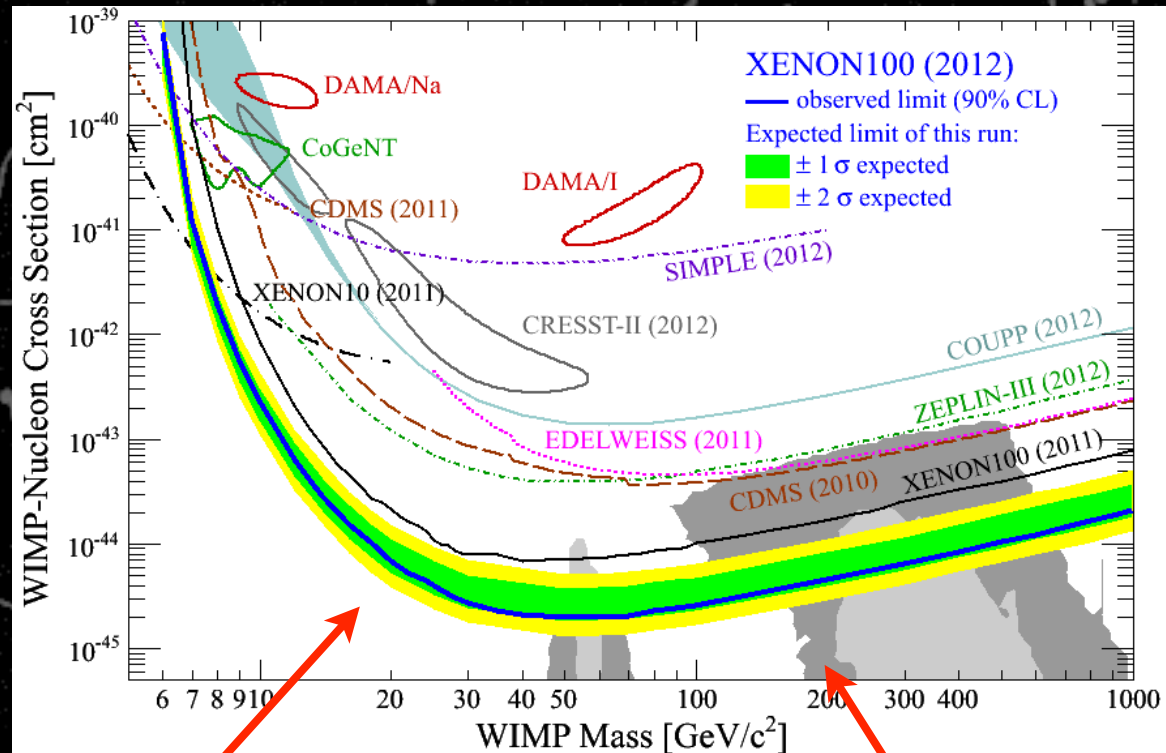


- ... but Xenon100, LUX exclude

Features of DM searches



Hints of signal at lower masses



CMSSM prefers heavy WIMPs ~200 GeV
 But ...
 increasingly ruled out by LHC & Xenon

Limited by energy threshold
 (need lower energy detection)

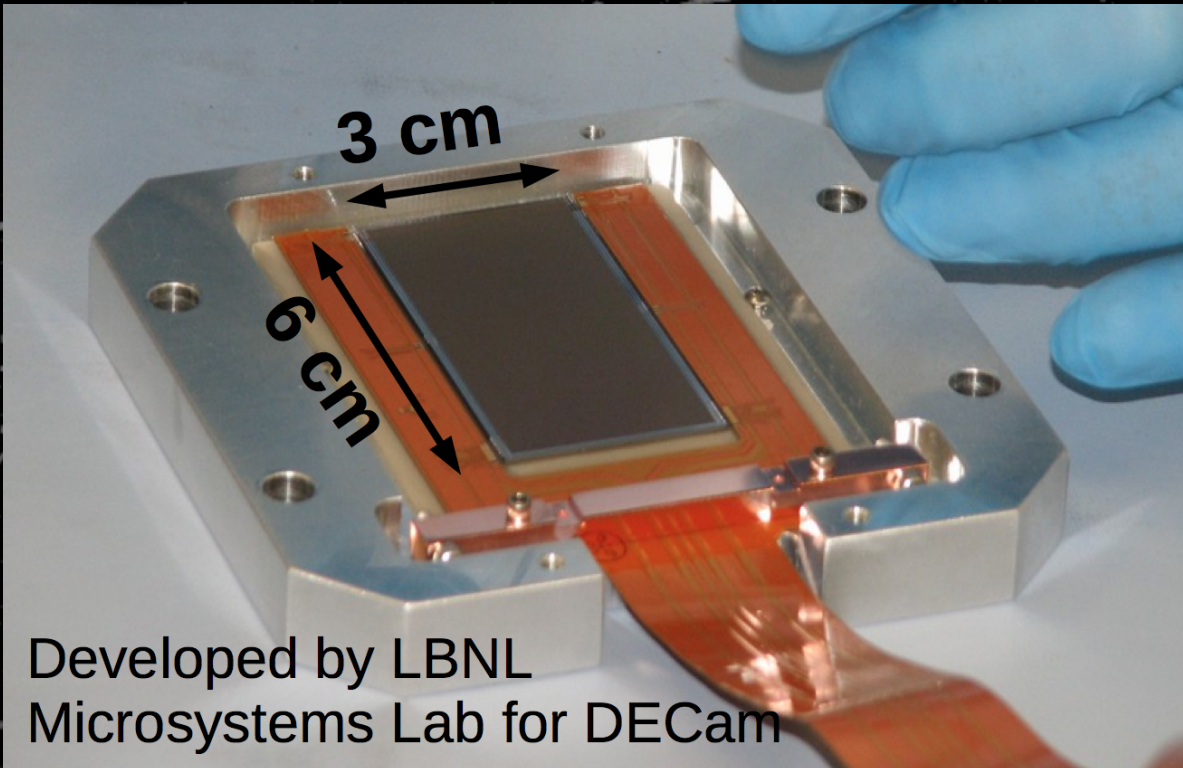
Limited by exposure mass
 (need bigger detector)
 multi-kg-sized detectors

Low mass (GeV) means low energy thresholds ...

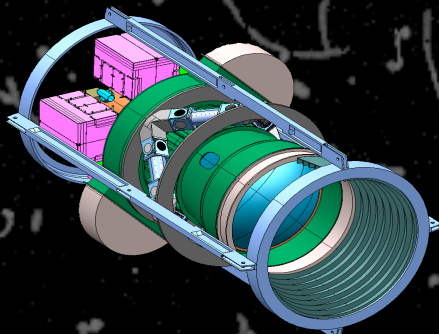
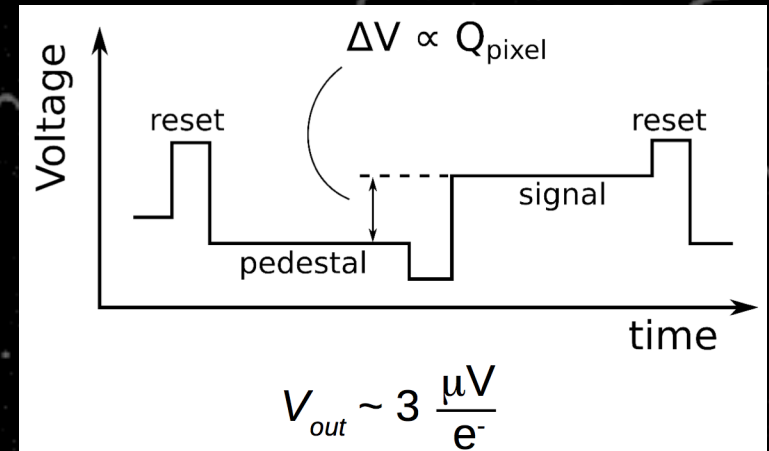
Experiment	Target	Exposure (kg-d)	Threshold	Ref
CDMS-SUF	Ge	65.8	5 keV	[2]
	Si	6.58	5 keV	
CDMS-II	Ge	121.3	10 keV	[3]
	Si	12.1	7 keV	[4]
XENON10	Xe	131	4.5 keV	[5]
CRESST-I	Al ₂ O ₃	1.51	0.6 keV	[16]

Can we get a factor of 10-100 lower than this ?

Scientific CCDs



One readout gate - all pixels shifted via phased potential wells and read out



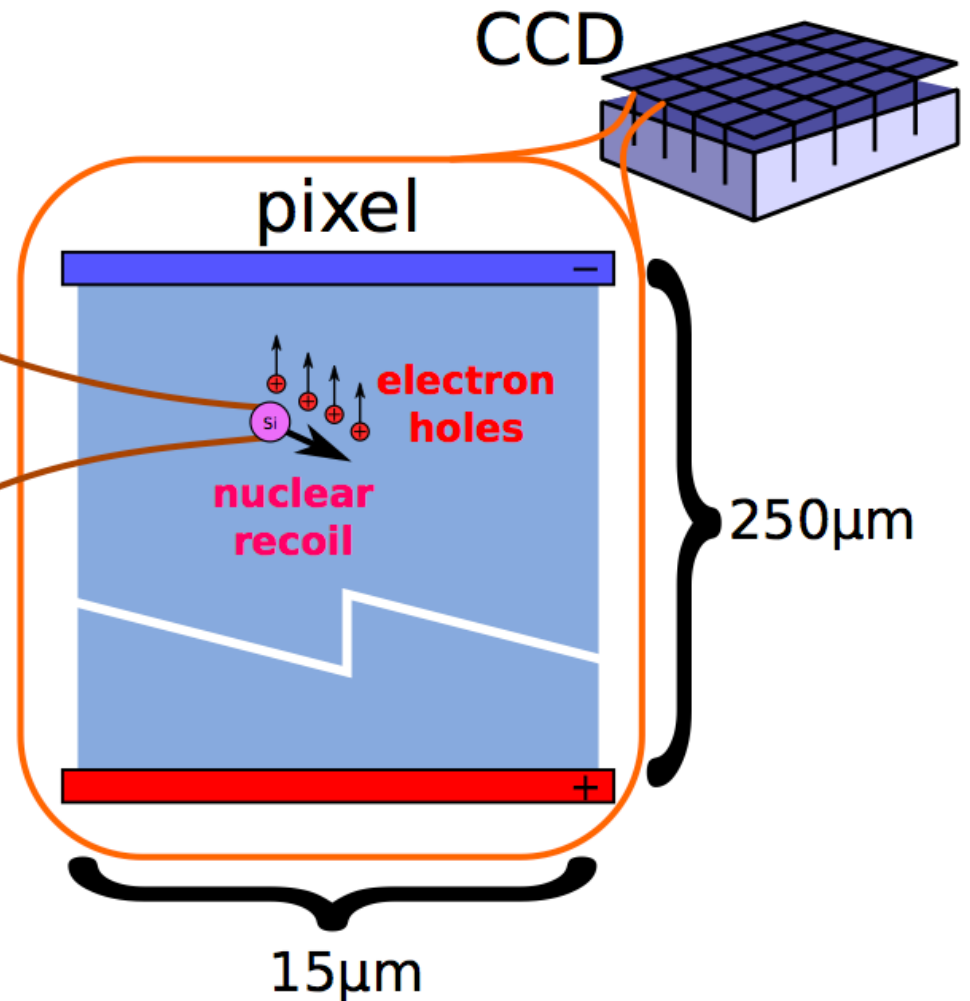
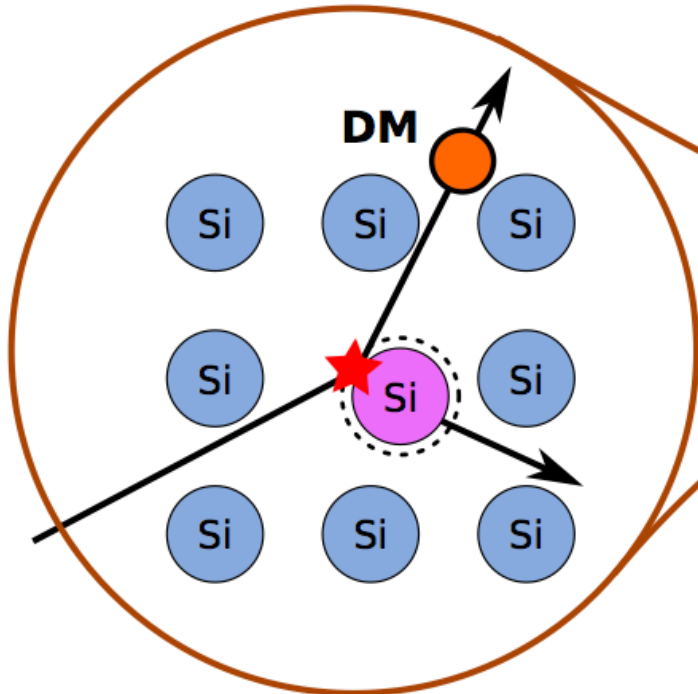
originally, LBNL for DES

- Pixel size: 15 μm x 15 μm
- Number of pixels: 2000 x 4000
- CCD Thickness: 250 μm
- CCD Mass: 1 gram
- Operation Temp: 150 K

Scientific CCDs for searching for DM



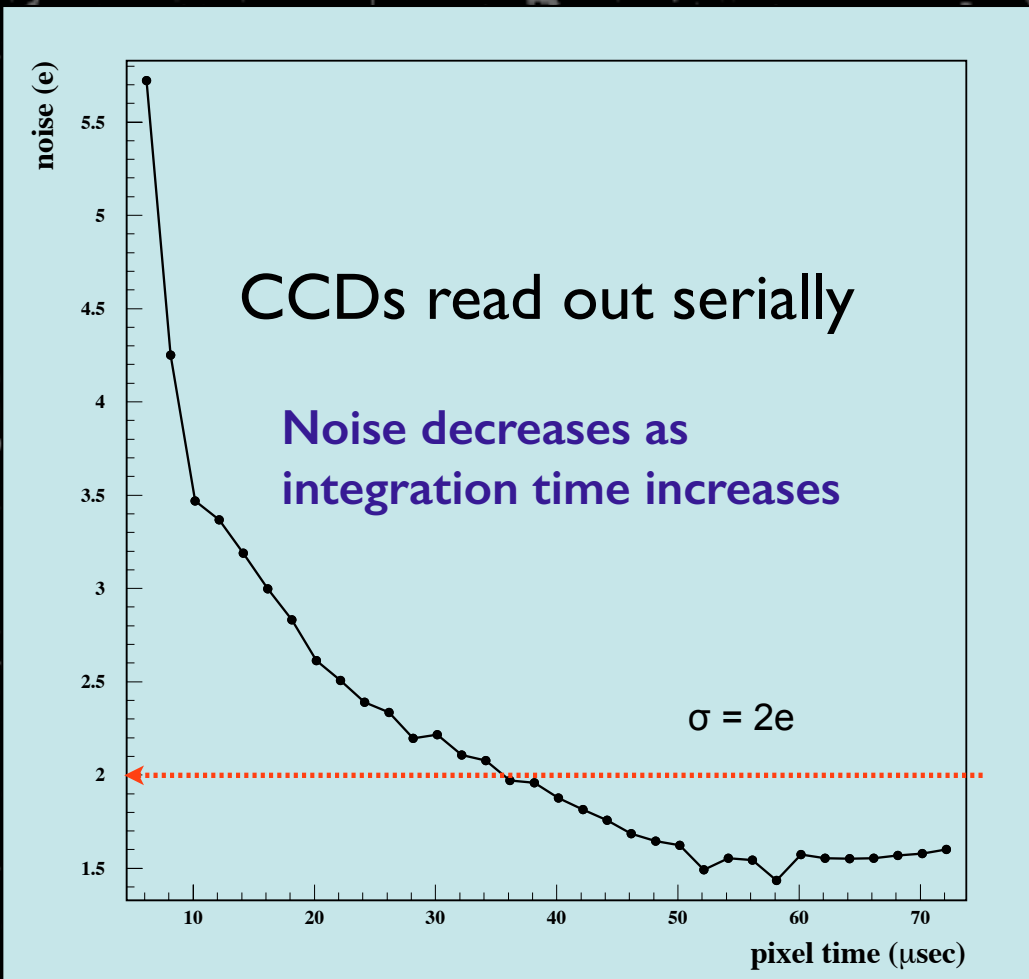
coherent elastic scattering



New opportunities with these CCDs

2. Low readout noise

- Detectors cooled to operate at -140 C
- Low threshold energy for detecting recoils



RMS noise of 2 electrons, or 7.2 eV in ionization energy !

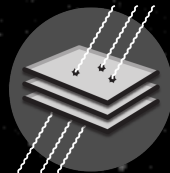
- At 5X the RMS noise, threshold: ~ 36 eVee

Experiment	Target	Exposure (kg-d)	Threshold	Ref
CDMS-SUF	Ge	65.8	5 keV	[2]
	Si	6.58	5 keV	
CDMS-II	Ge	121.3	10 keV	[3]
	Si	12.1	7 keV	[4]
XENON10	Xe	131	4.5 keV	[5]
CRESST-I	Al ₂ O ₃	1.51	0.6 keV	[16]



(This background is a CCD image)

Particle identification in CCD



alpha



electrons



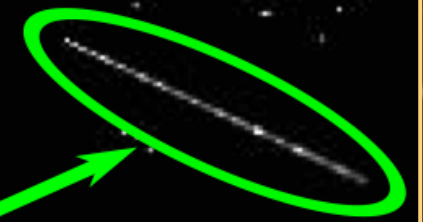
X-rays



diffusion limited hit

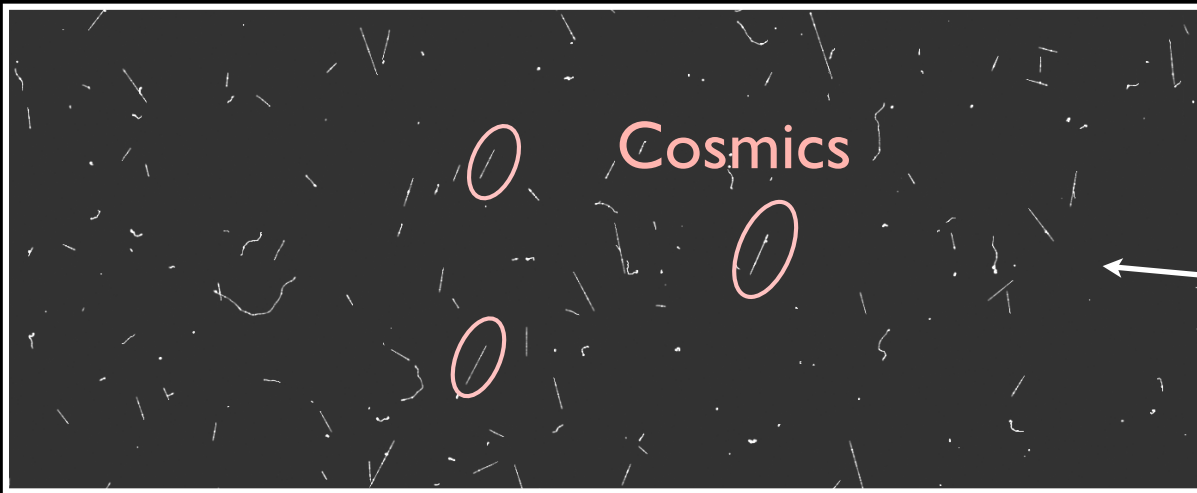


muons



100 pixels
1.5 mm

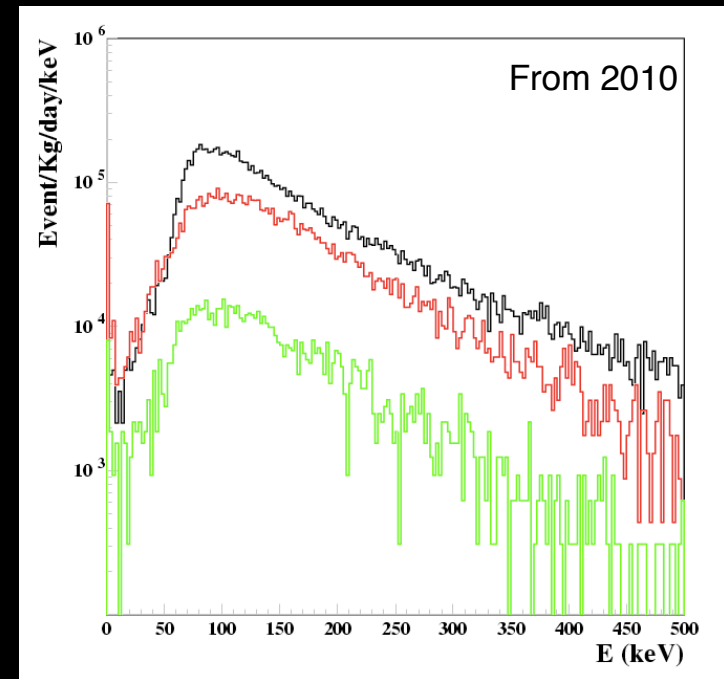
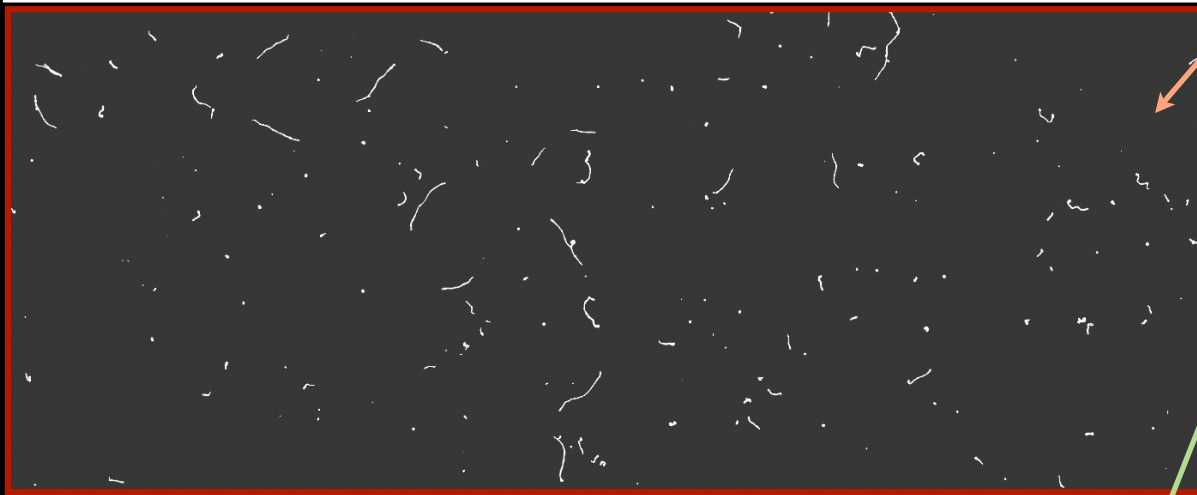
Background reduction



Above ground

350 ft underground

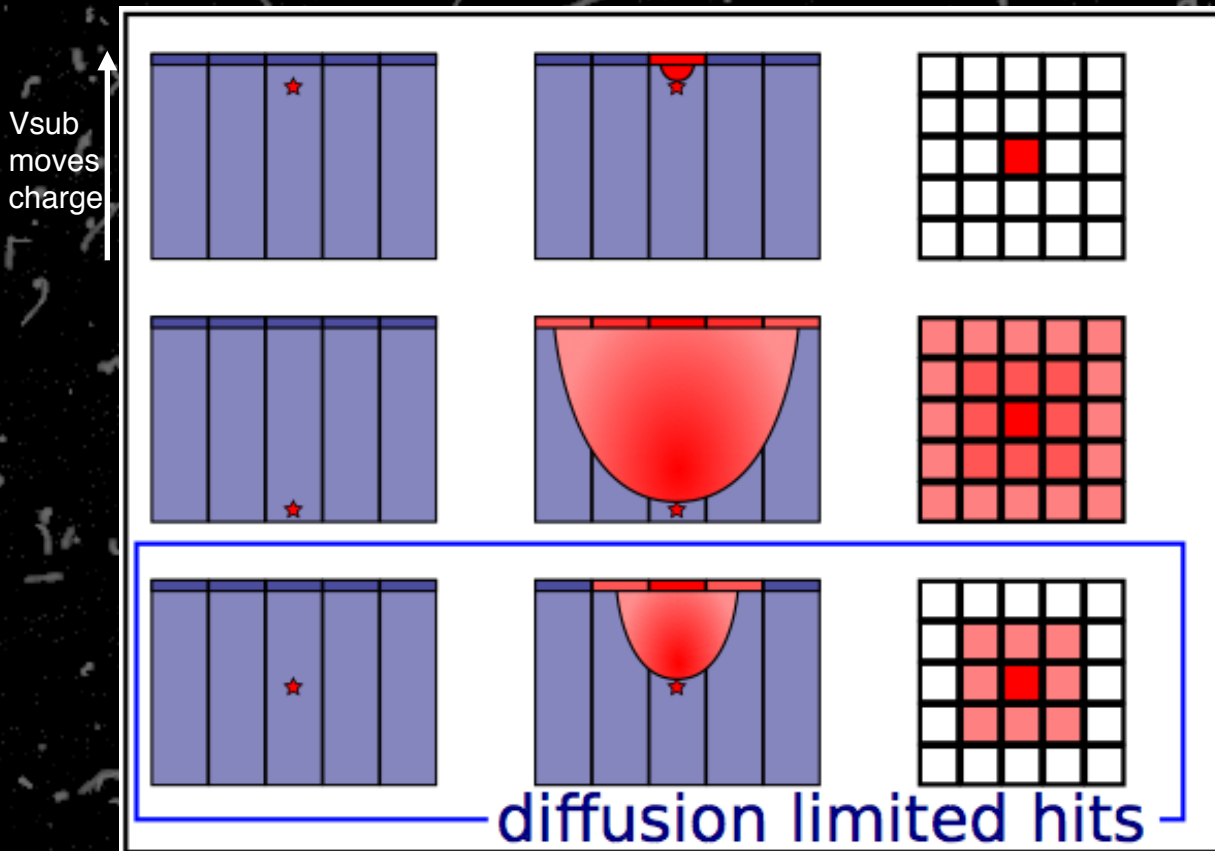
With lead brick shielding



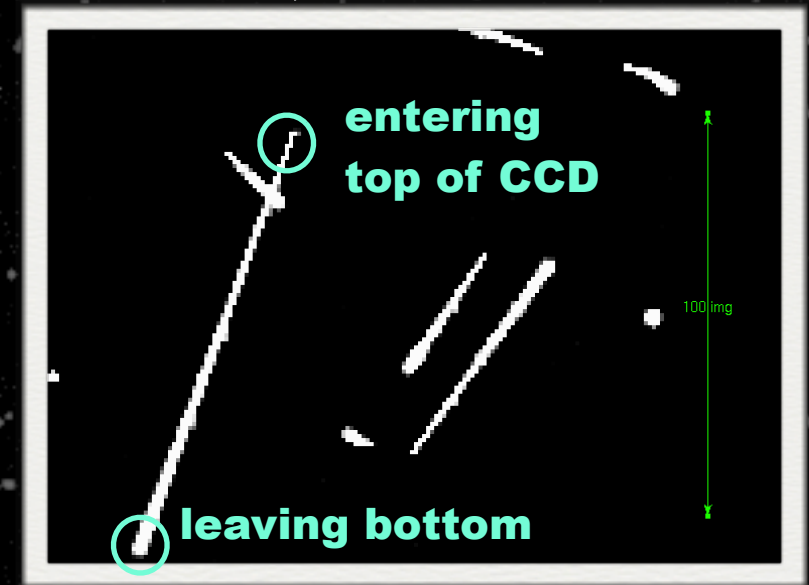
Diffusion of charge



- **Size of hit depends on location within pixel**

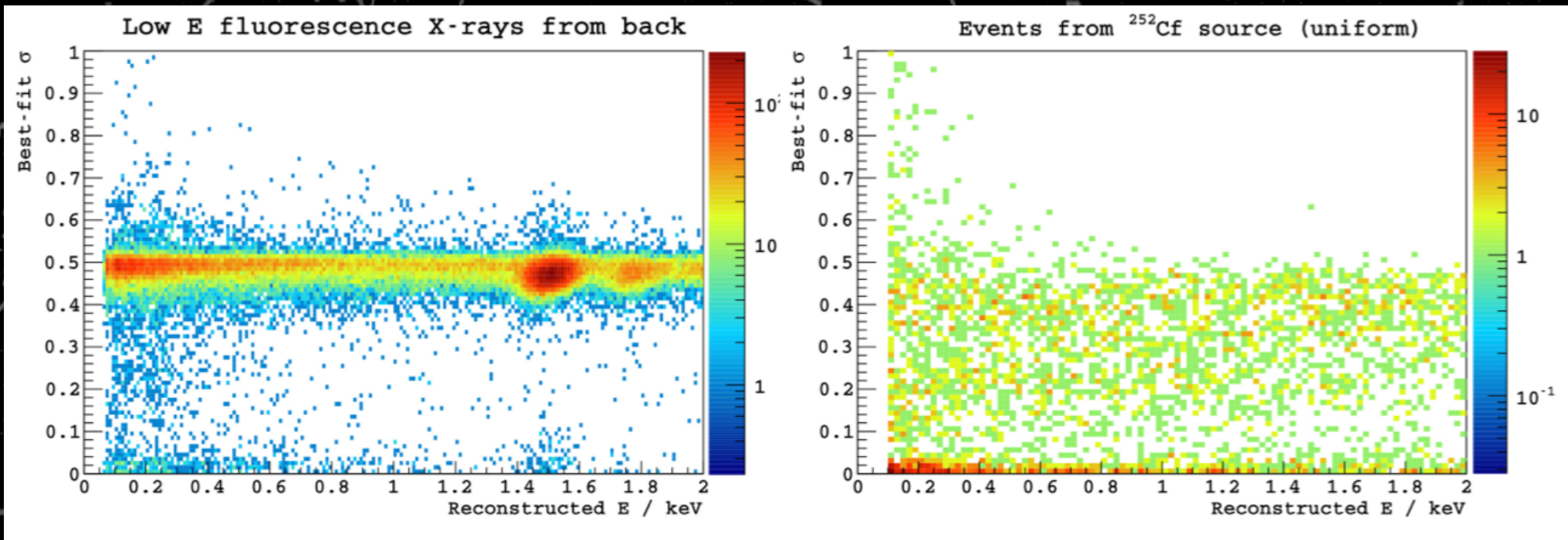


ie, muons



- **Maximal (minimal) diffusion at bottom (top) of CCD**

X-rays vs neutrons



X-rays
bkg-like

Neutrons
“DM-like”

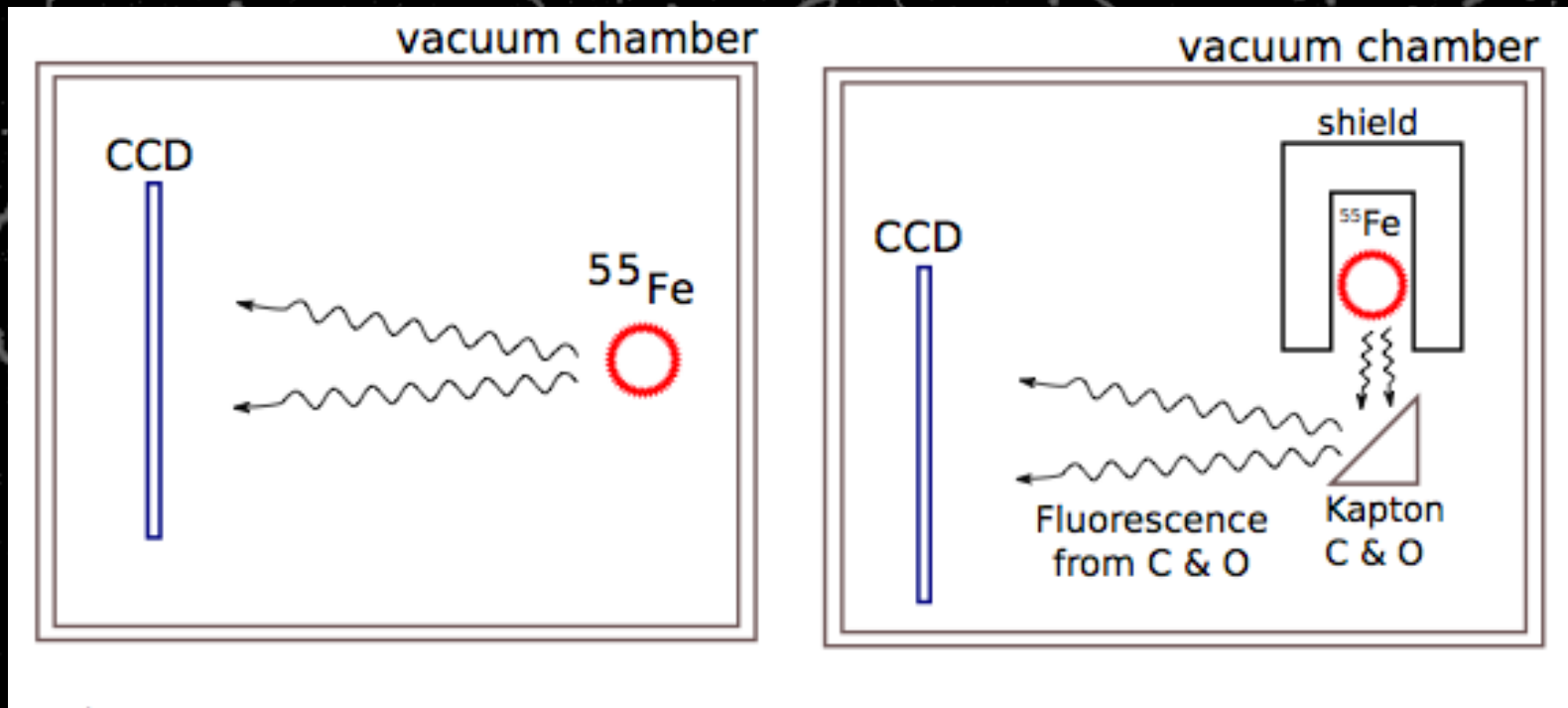
- Maximal diffusion $\sim 7\mu\text{m}$ (0.5 pixel) RMS
- Can be used to reject surface events

Calibrations

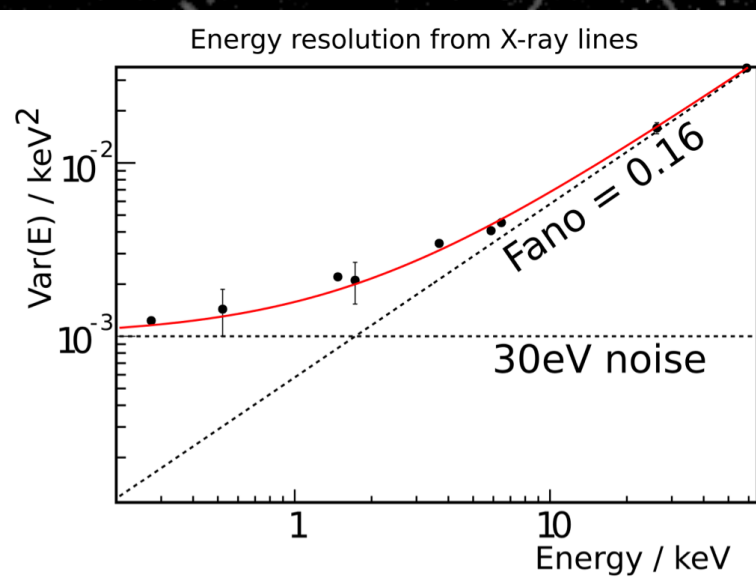
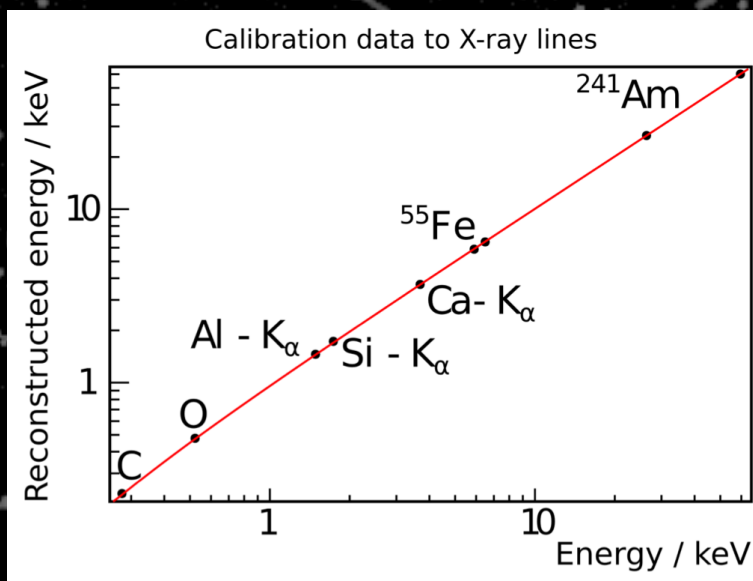
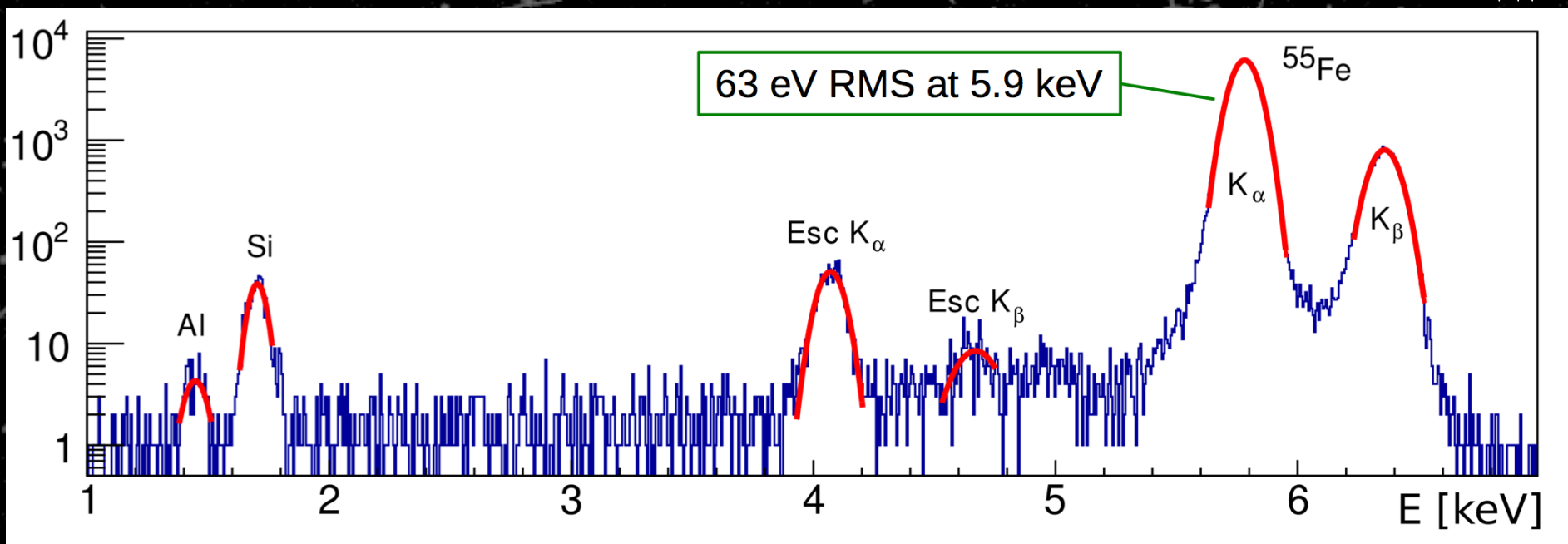
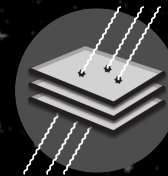
Energy calibration



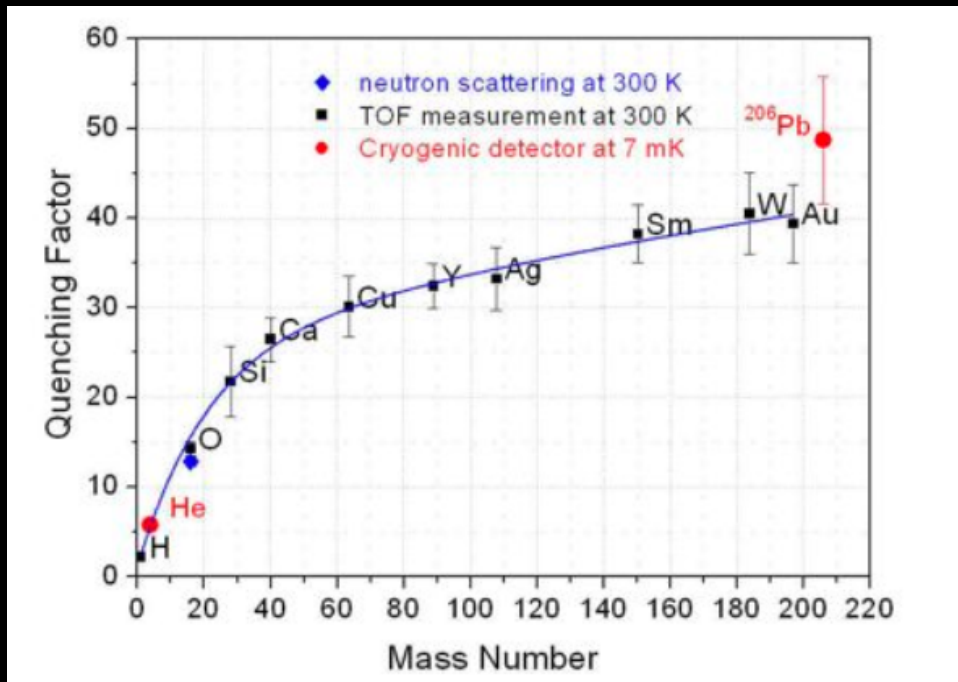
- **X-rays and fluorescence X-rays**



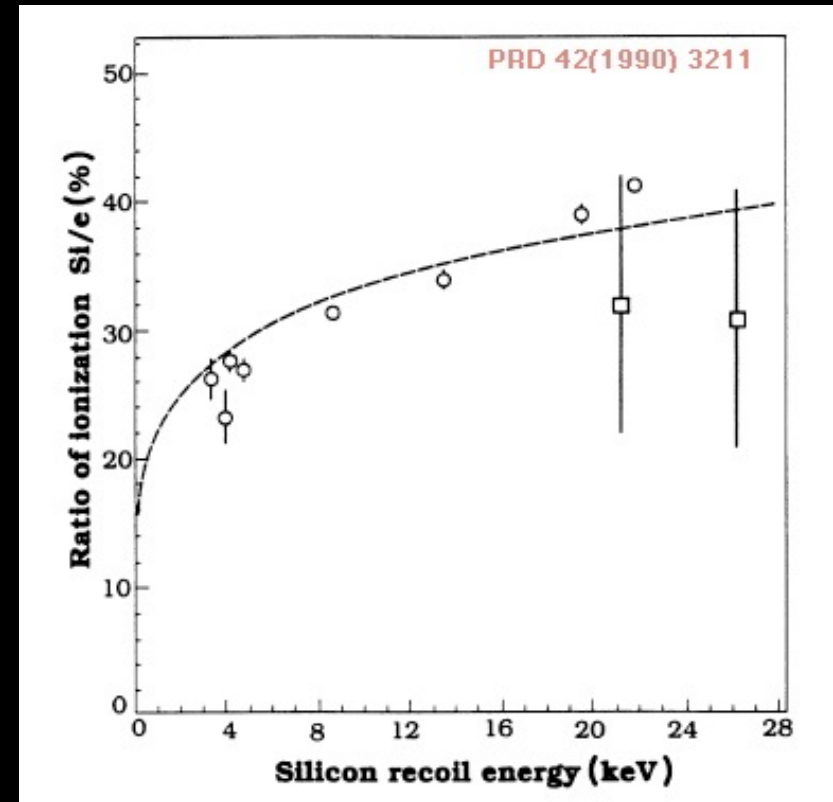
Calibrations with X-rays



Nuclear recoils from DM are different



Fraction of observed energy :
“Quenching factor” depends on
Mass Number ...



... but also on recoil energy :

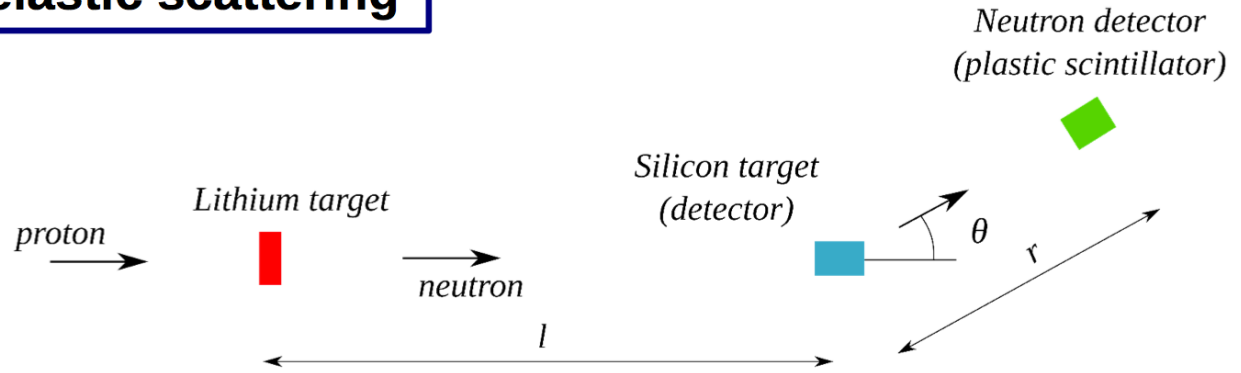
Note lack of data below 4 KeV

1 KeV range nuclear recoils



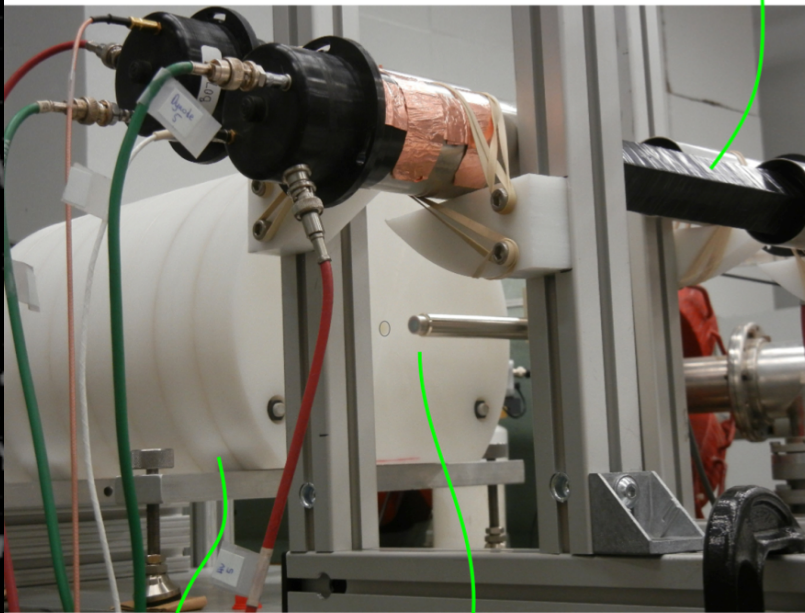
Fast neutrons elastic scattering

$E_p = 2.3 \text{ MeV}$
 $E_n \text{ in } [100, 600] \text{ keV}$



University of Notre Dame
(Indiana, USA)

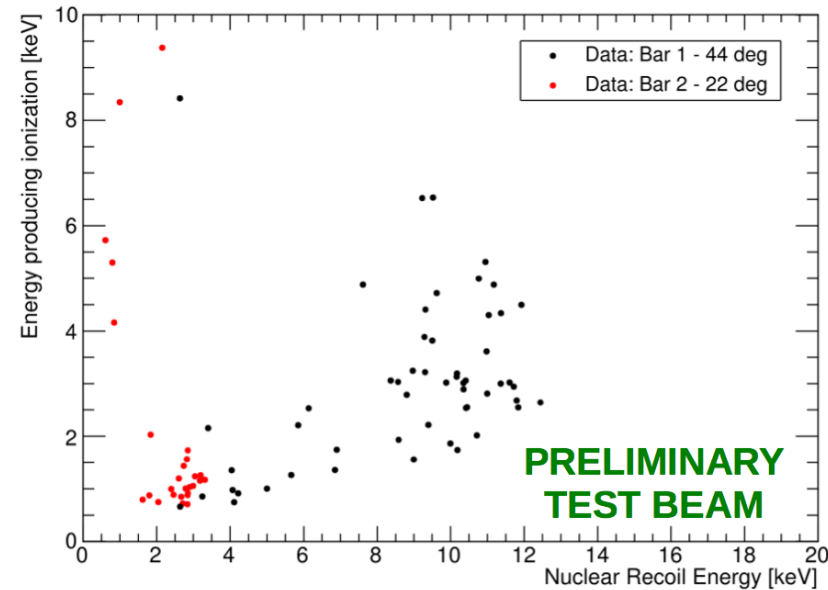
Scintillator Bar



Collimator

Silicon Detector

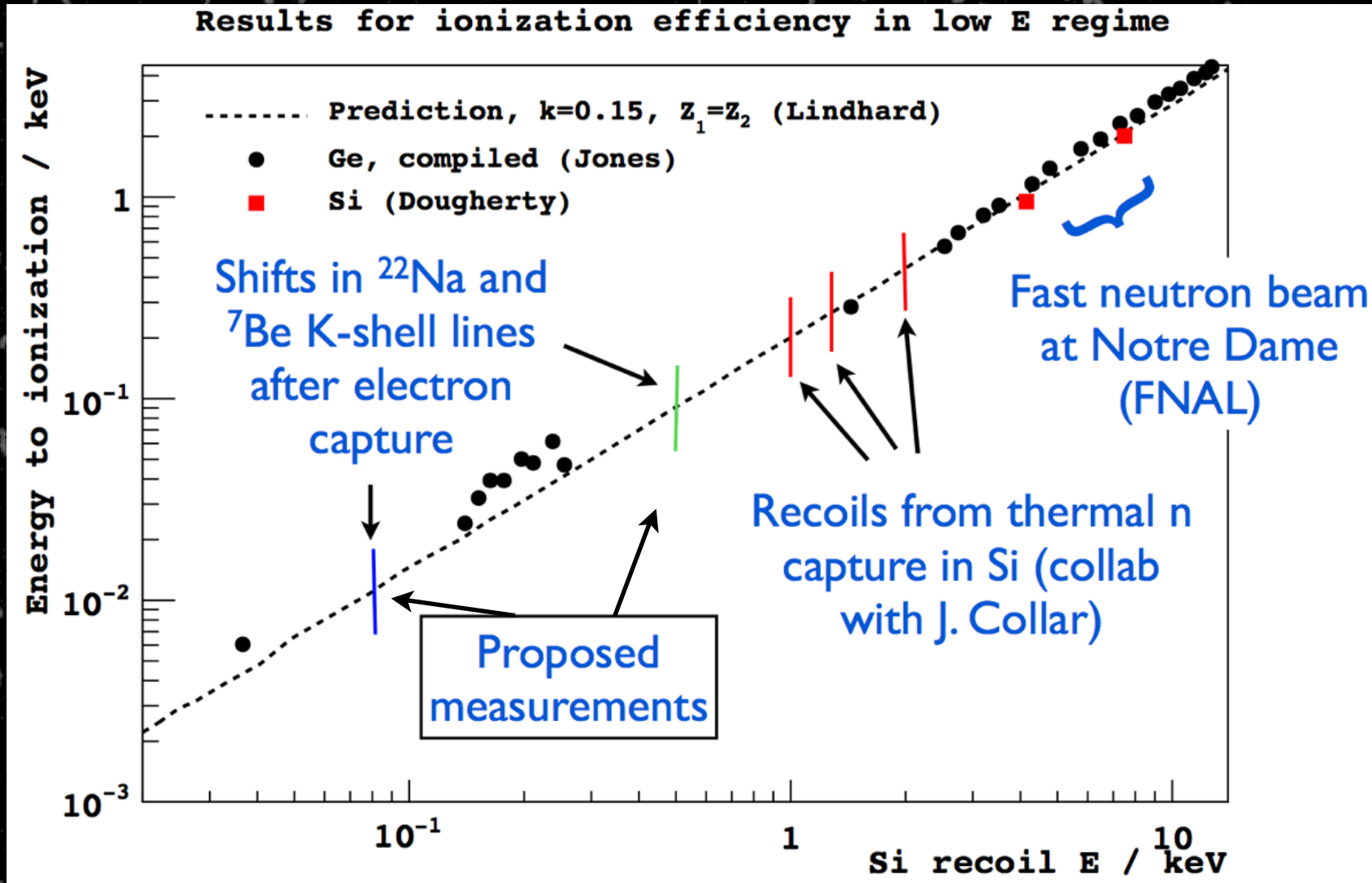
Energy producing ionization vs Nuclear Recoil Energy



PRELIMINARY
TEST BEAM

Ionization efficiency for nuclear recoils

- Challenge is to provide dependable calibration down to 50 eV energy threshold

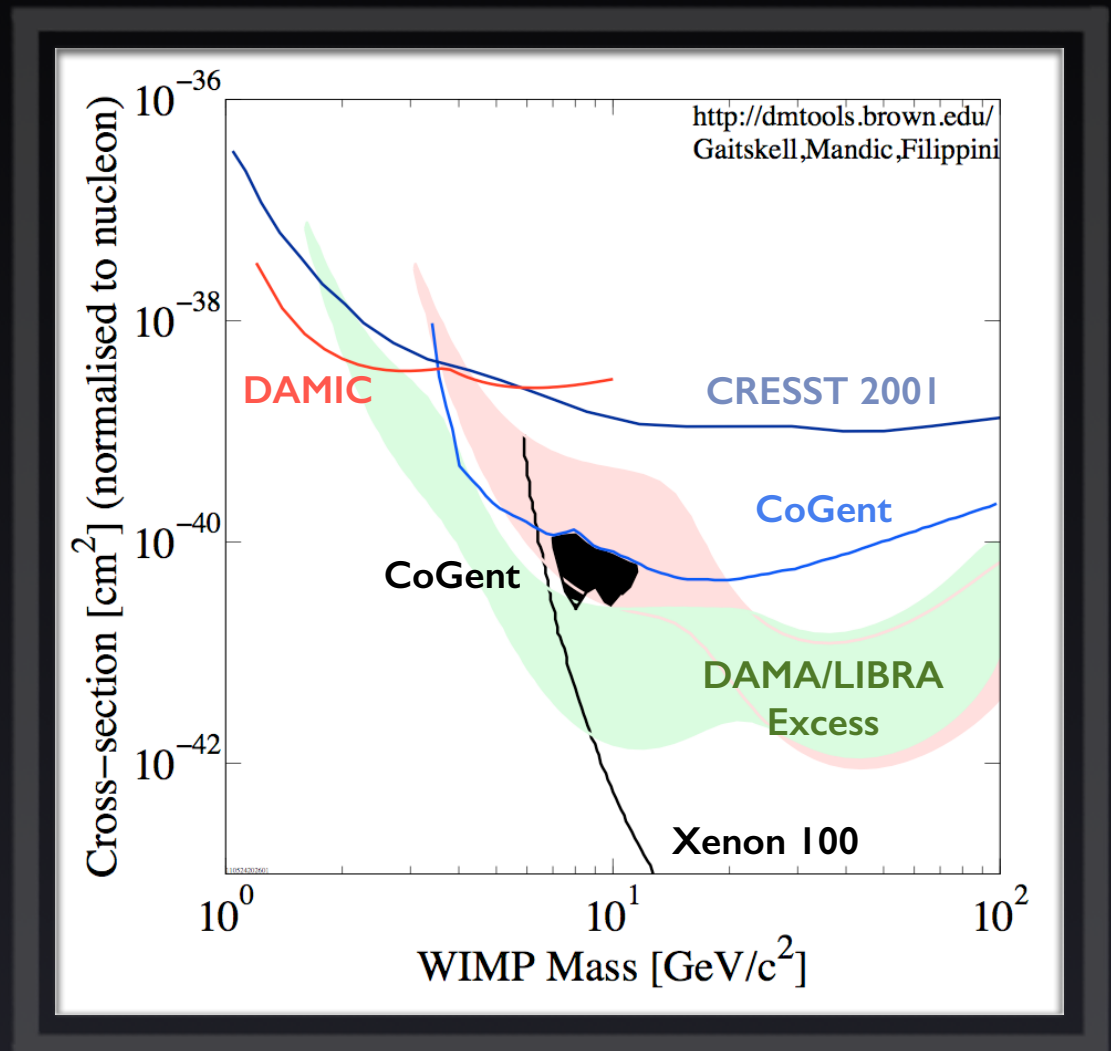


DAMIC experiment

Results from DAMIC 2011

- **Depth of 350 feet**
- **107 g-days**
- **In 2012, best low mass limit**

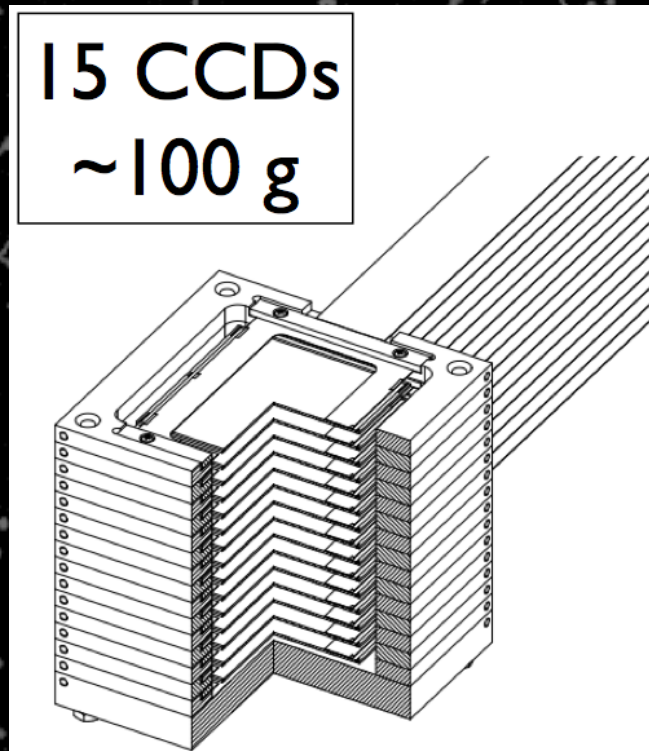
Assumes Lindhard quenching factor
for conservative limits



Upgrading DAMIC



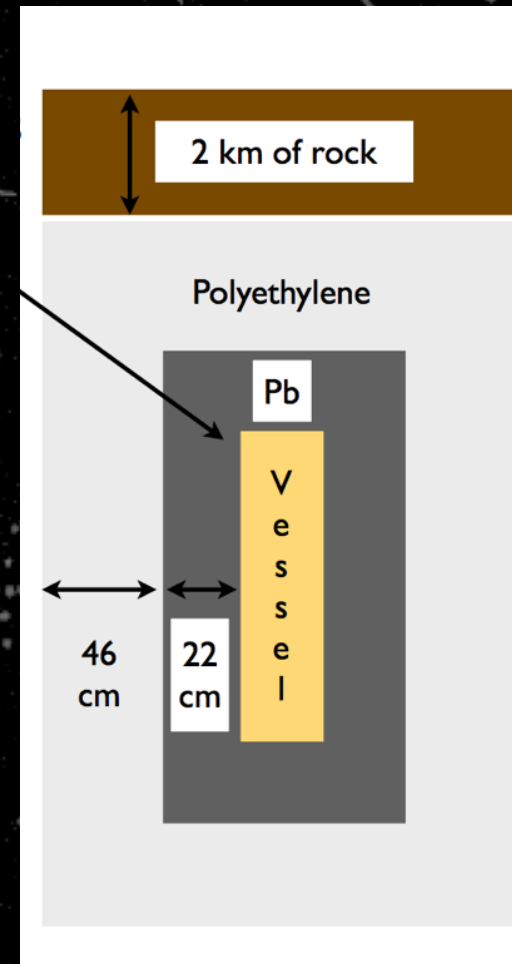
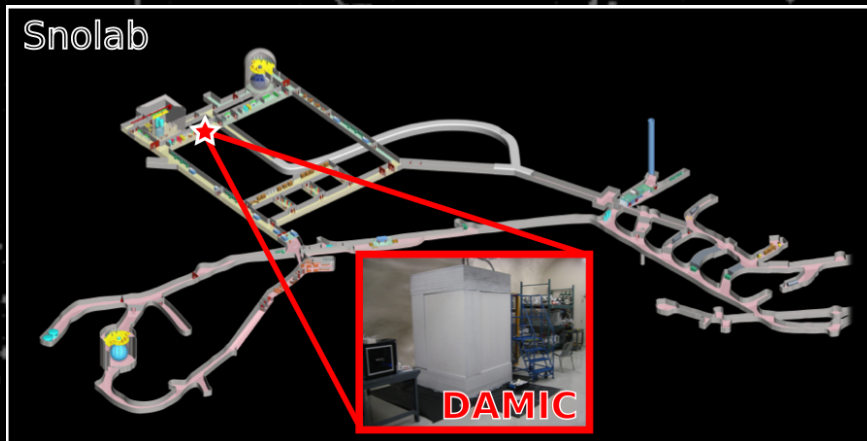
- **LBNL CCD group has produced thicker, fully depleted high resistivity CCDs (650 μm)**
 - **DAMIC 2011 used 250 μm (normal CCD \sim 25 μm)**
 - **Can now reach 100 g of detector mass**



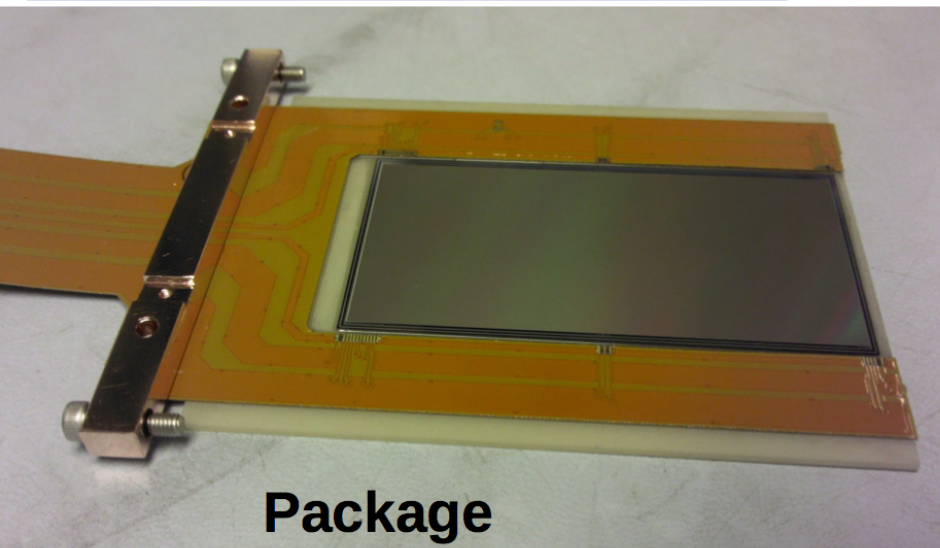
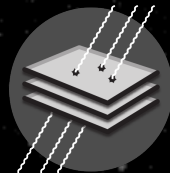
Improved shielding ...



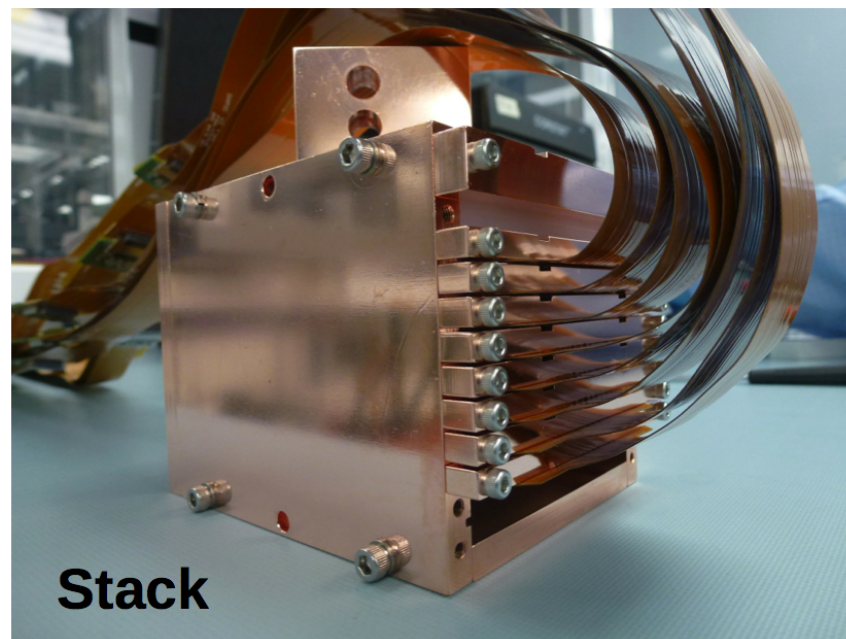
- **DAMIC prototype in operation at SNOlab**



DAMIC: at SNOLAB (2013)



Package



Stack



Dewar

DAMIC: at SNOLAB (2013)

HDPE shield



Vacuum
Cryocooler
DAQ

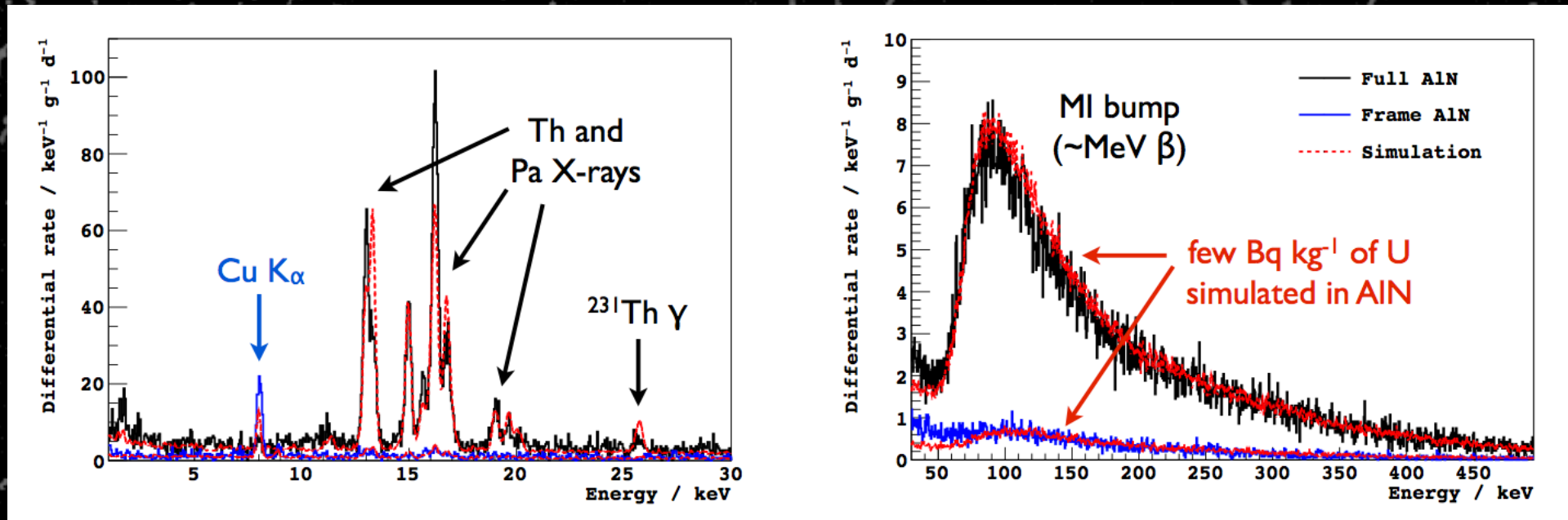
Lead castle



First DAMIC data @ Snolab



Found contamination of Uranium 238 decay chain in CCD frame



Red is simulation

New frame (blue) design solves this background ...

DAMIC 100 - begins in ~3 months



Collaboration :
Fermilab
U. Chicago
U. Zürich
U. Michigan
UNAM
FIUNA
CAB

DAMIC100

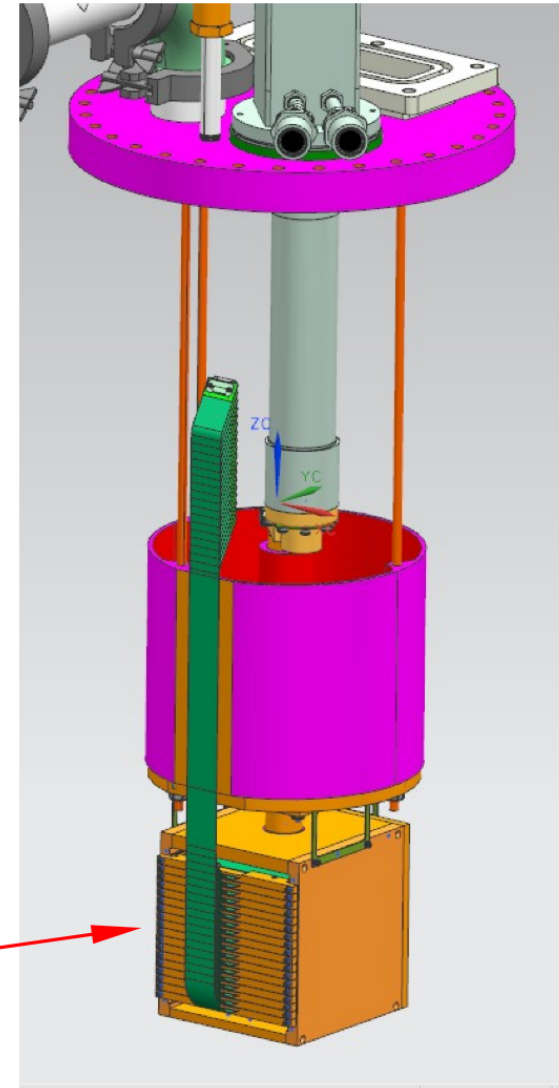
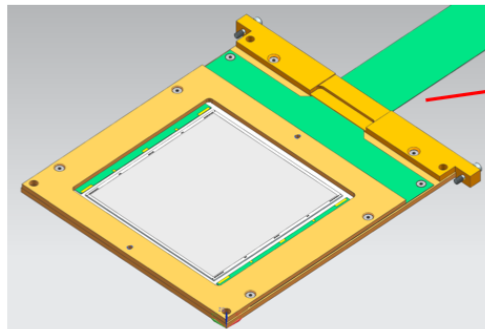
Under construction now

- 100 g of Silicon active mass
- 18 CCDs
 - 5.5 g
 - 6 cm x 6 cm
 - 650 μm thick
- Fits in existing Dewar and Shield
- Background

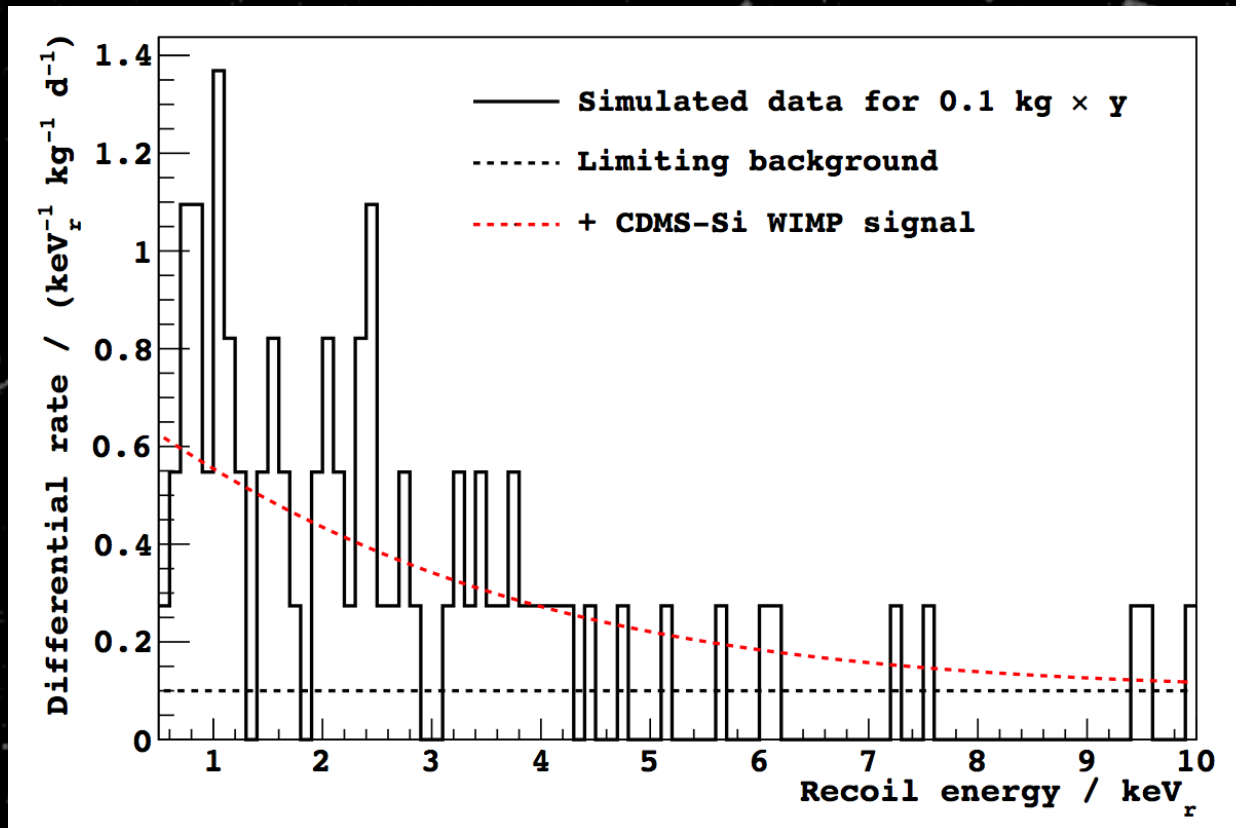
Current: 100 events/(kg day keV_{ee})

DAMIC100: few events/(kg day keV_{ee})

- Lead upgrade:
low Pb-210 + ancient
- CCD package
high resistivity silicon



Simulation of DAMIC 100

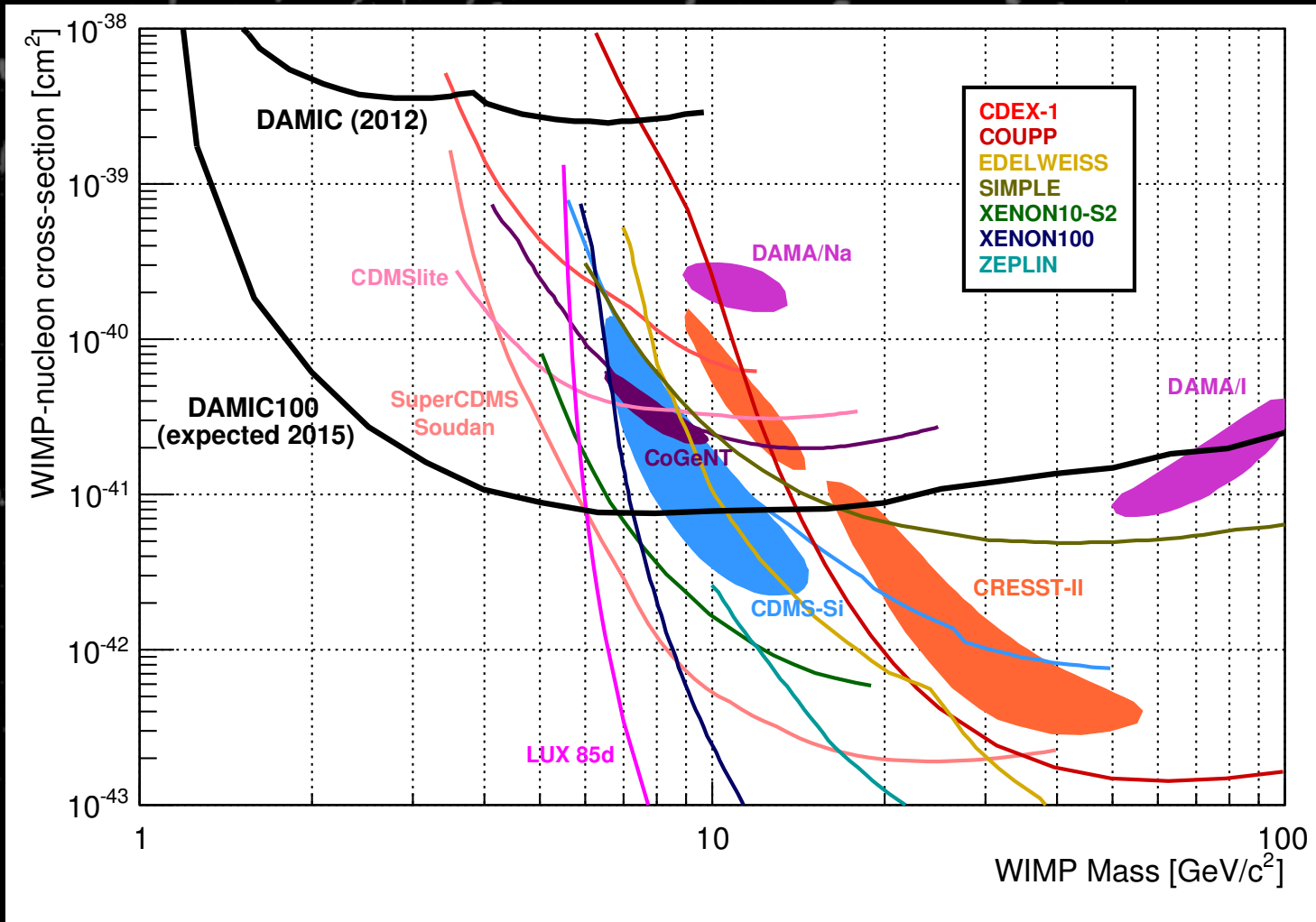


- **Using MCNPX simulation and radioactive screening measurements**
 - **Assumes 0.5 dru (events/kg/day/keVee)**
 - **0.30 ± 0.07 dru : gammas - from electronics above lead in vessel (vacuum interface board)**
 - **Cosmogenic activated Co-58, Cu-60 in copper shielding : < 4 dru**
 - **238U & 40K in Kapton cable : < 1.5 dru**

Sensitivity



- **Projected DAMIC 100 with 1 year of data**



2012 DAMIC limit 107 g-days
with 0.04 keV energy threshold
Phys.Lett. B711 (2012) 264-269

- **Will test much of low mass interesting region**

Future

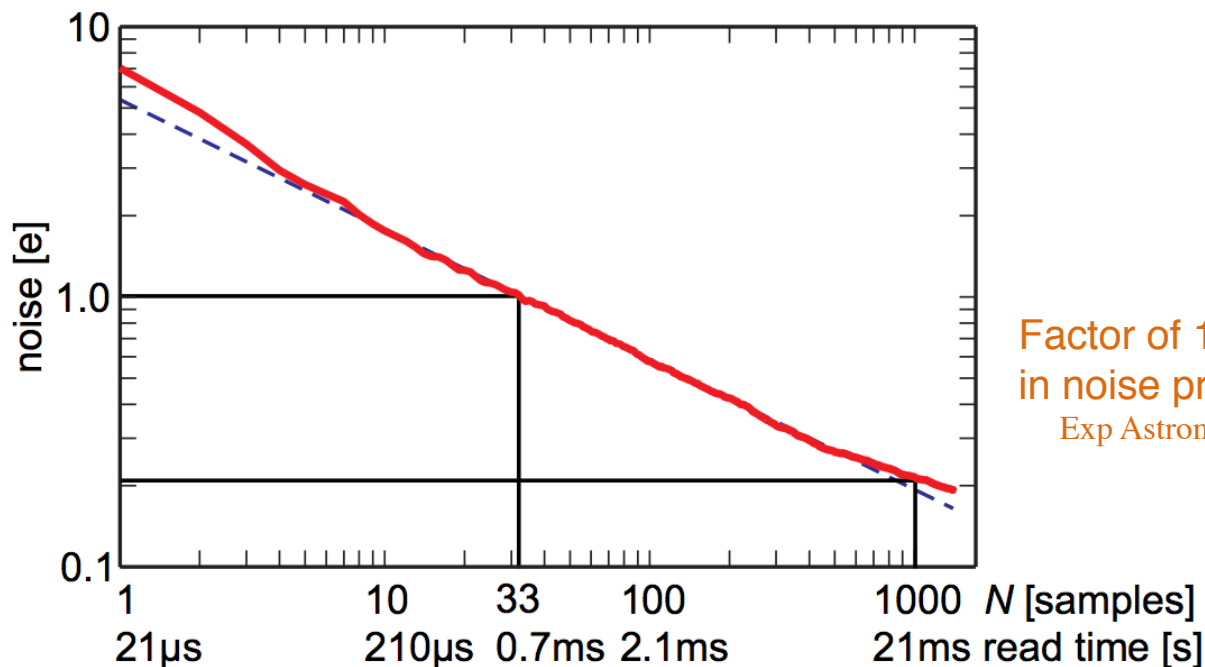


Lowering the noise: Skipper CCD

- Main difference: the CCD allows multiple sampling of the same pixel without corrupting the charge packet.

- The final pixel value is the average of the samples

$$\text{Pixel value} = \frac{1}{N} \sum_i^N (\text{pixel sample})_i$$



Factor of 10 reduction
in noise proven
Exp Astron (2012) 34:43–64

0.2 e- noise !

Summary

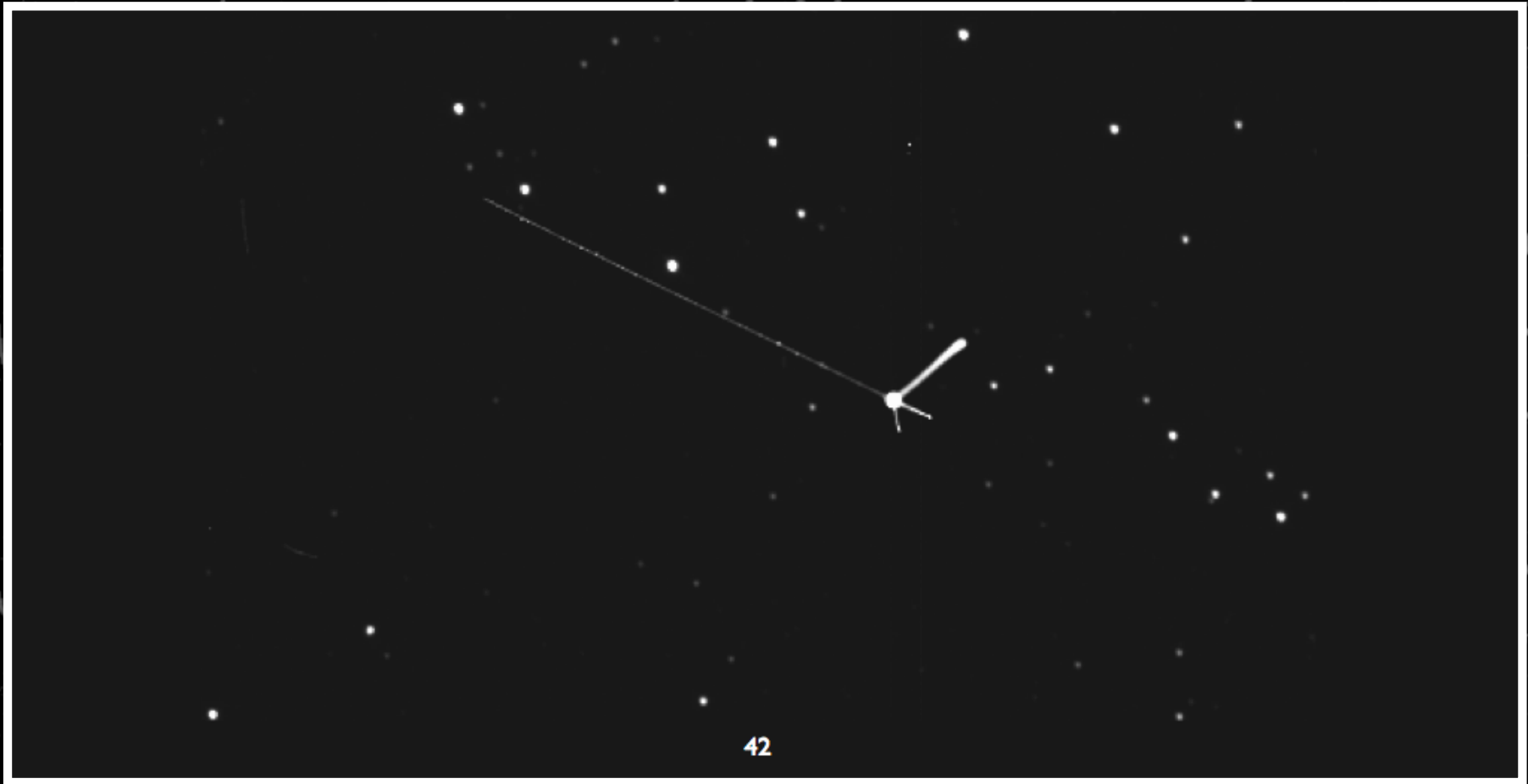


- **Low mass dark matter ~ 5 GeV**
 - **Experimental hints ?**
 - **Theoretically motivated**
 - **But low energy threshold difficult**
- **CCDs**
 - **Achieves very low energy threshold**
 - **Can do factor of ten better**
 - **Requires strong calibration effort & bkg understanding**
- **DAMIC 100 begins this summer**
 - **Will provide strong constraints for low mass dark matter in ~ 1 year**

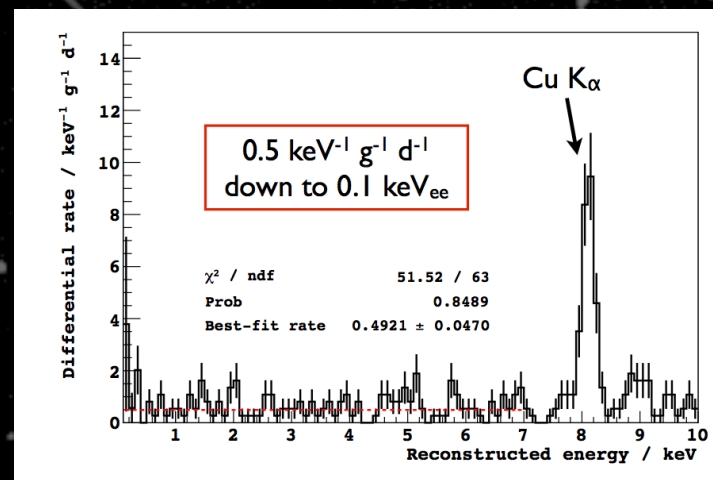
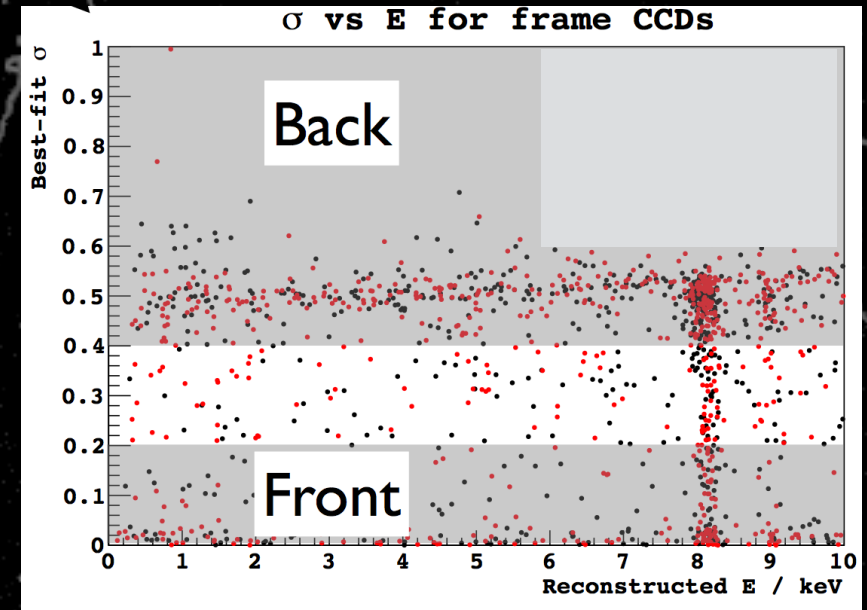
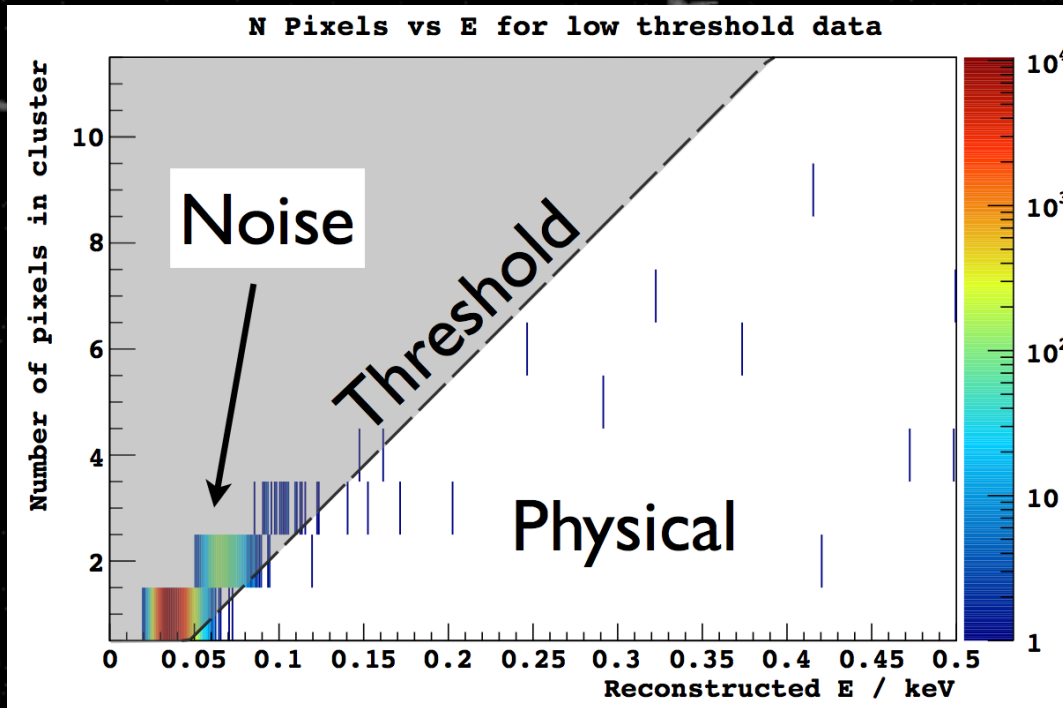


BACKUPS

An interesting event



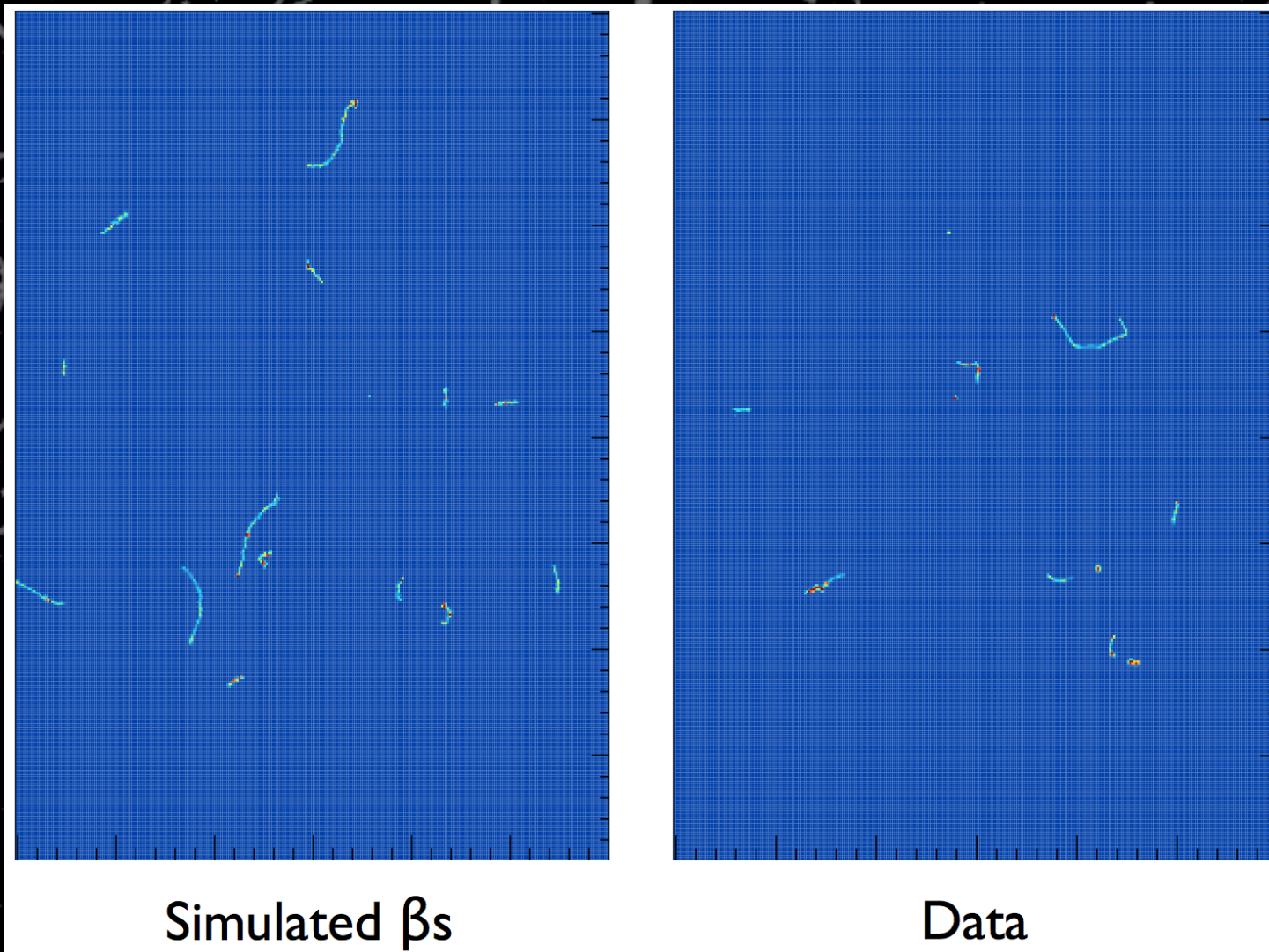
First DAMIC data @ Snolab



Interactions can be simulated



- **MCNPX simulation -> background model**



Simulated β s

Data

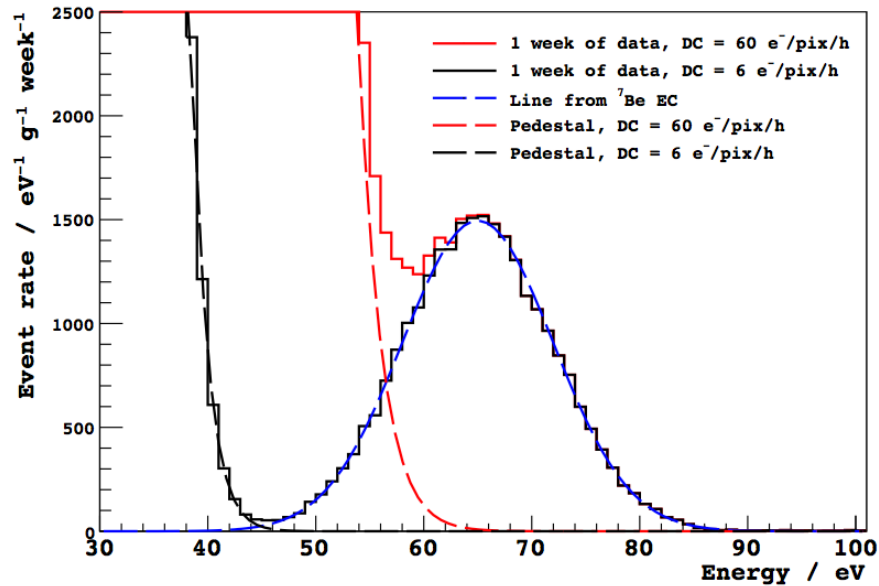
Getting to lower energies



- **Irradiate CCD with protons ($2E10$ @ 230 MeV)**
- **Activates ^7Be and ^{22}Na uniformly in CCD**
- **These decay by electron capture**
 - **Nominally emits 54 eVee & 849 eVee photons**
 - **But small energy shift due to nuclear recoil**
- **Precisely measure photons**
 - **Shift tells you nuclear recoil calibration**
 - **Momentum conservation !**



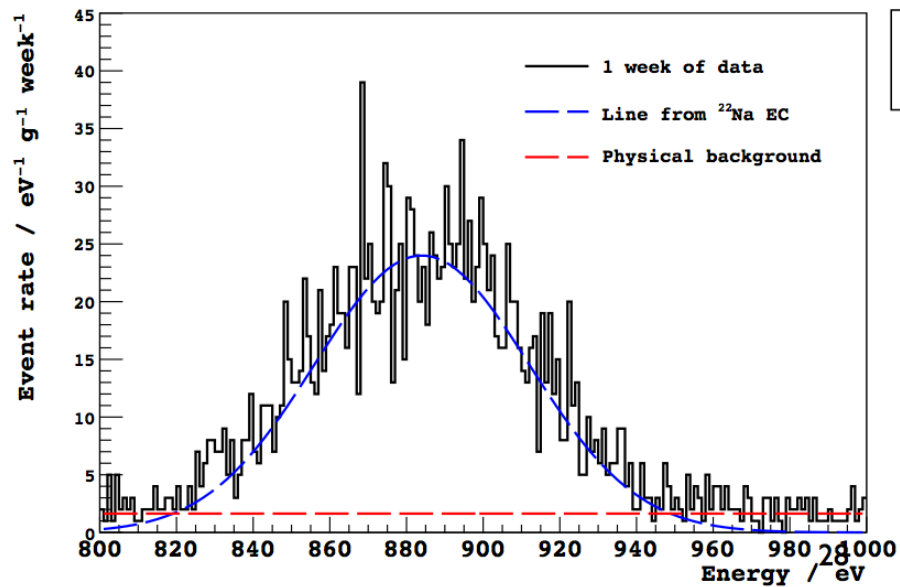
CCD spectrum 60 days after 10^{10} protons cm^{-2} exposure



${}^7\text{Be}$ EC

55 eV shifted to 65 eV for $Q \sim 10\%$

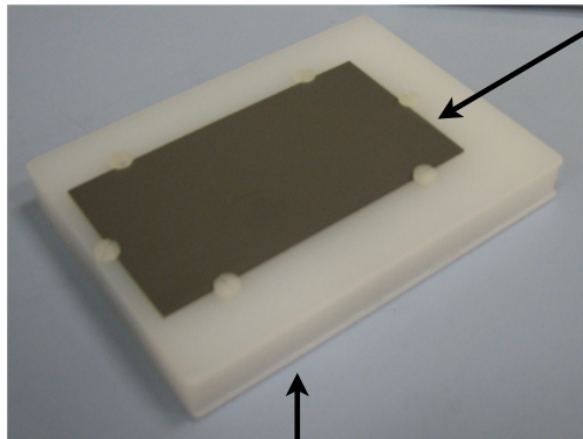
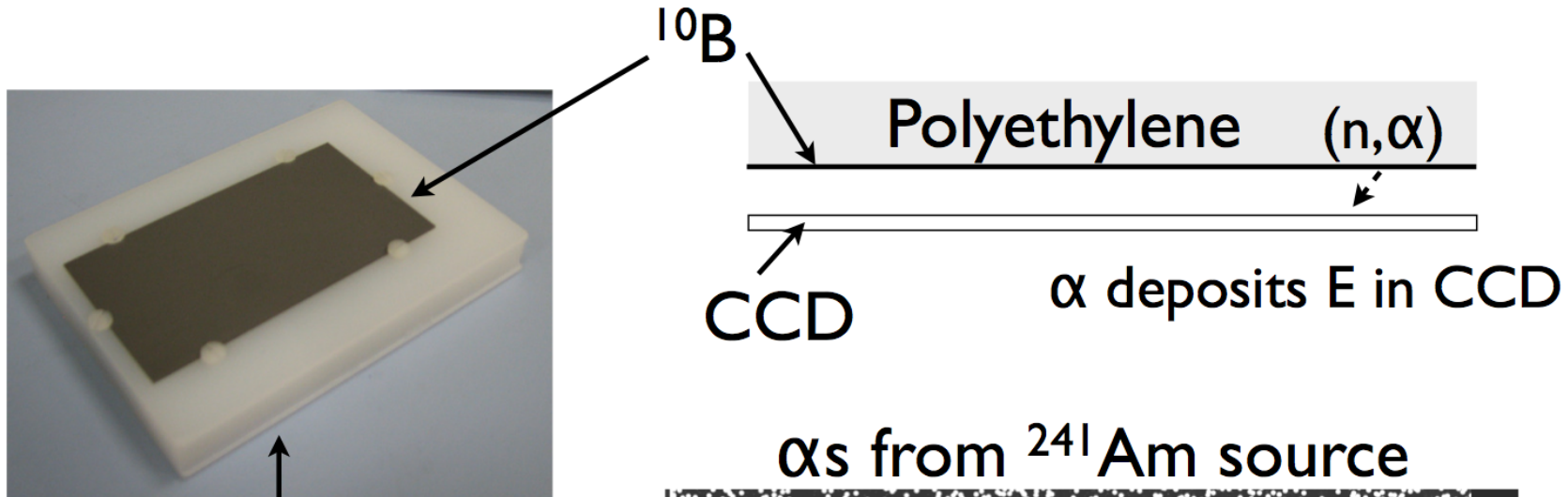
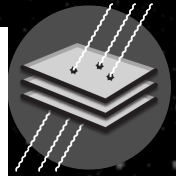
CCD spectrum after 10^{10} protons cm^{-2} exposure



${}^{22}\text{Na}$ EC

870 eV shifted to 884 eV for $Q \sim 10\%$

In-situ neutron background estimate



Slides into Cu box at SNOLAB

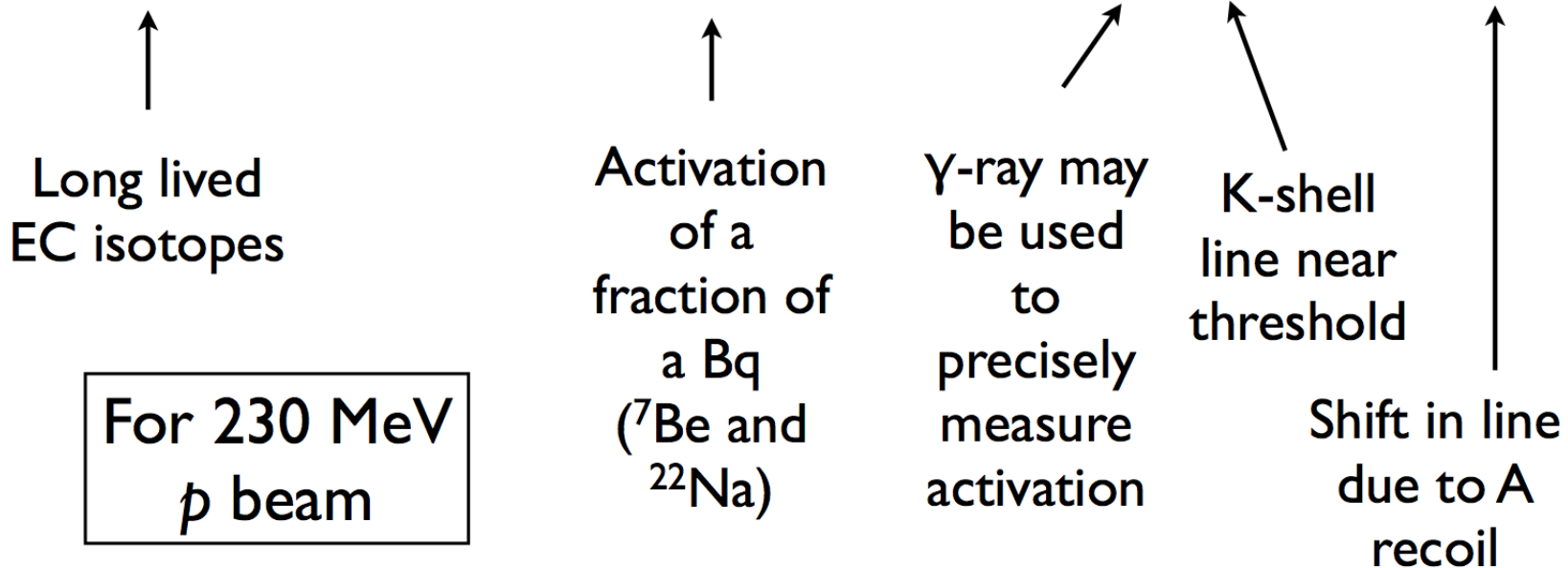
Test performed at FNAL this summer

Nucl.Instrum.Meth. A665 (2011) 90-93



CCD activation at a proton beam

Isotope	Half-life days	Si(p,x) mb	Activation	EC prob.	$\frac{E_\gamma}{\text{keV}}$	$\frac{E_K}{\text{eV}}$	$\frac{\sigma_K}{\text{eV}}$	$\frac{E_R}{\text{eV}}$	$\frac{\delta E}{\text{eV}}$
			$\text{Bq g}^{-1} (10^{10} \text{ p cm}^{-2})^{-1}$						
${}^7\text{Be}$	53.12	3.2	0.103	1.000	477.6	55	7	57 + 0	10
${}^{22}\text{Na}$	950.3	15.8	0.029	0.097	1275	870	28	60 + 40	14

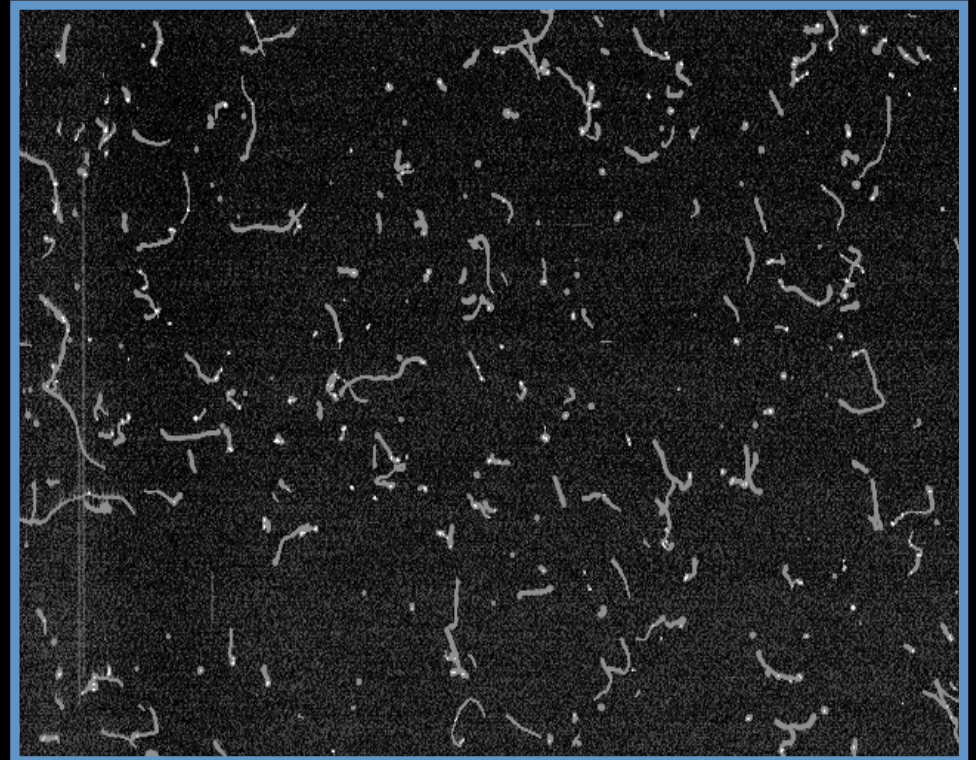


X-ray ^{55}Fe (5.9 keV)



Point like hits
(diffusion limited)

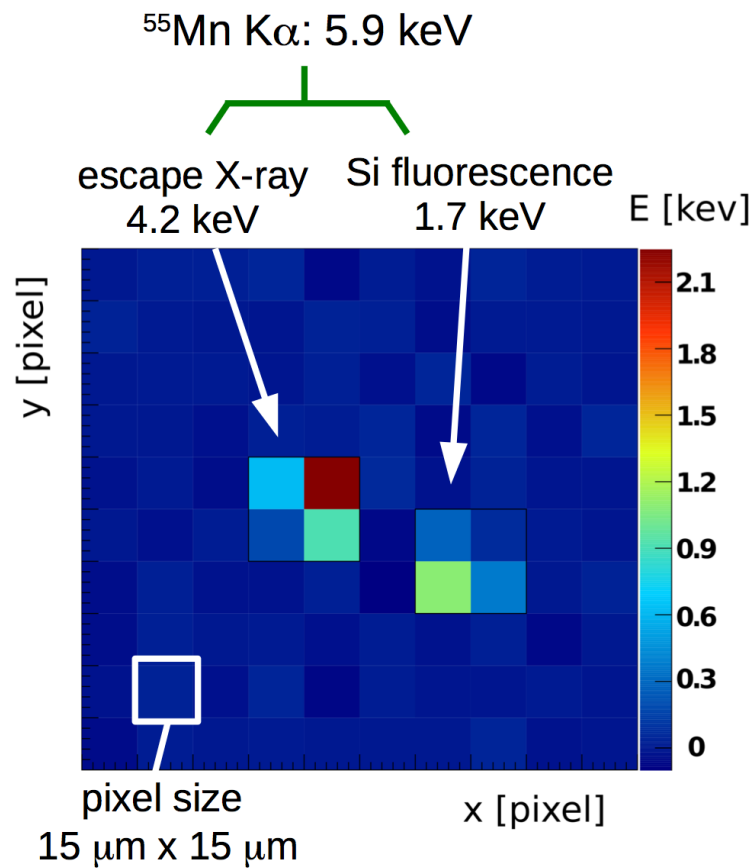
Gammas ^{60}Co (1.33 & 1.77 MeV)



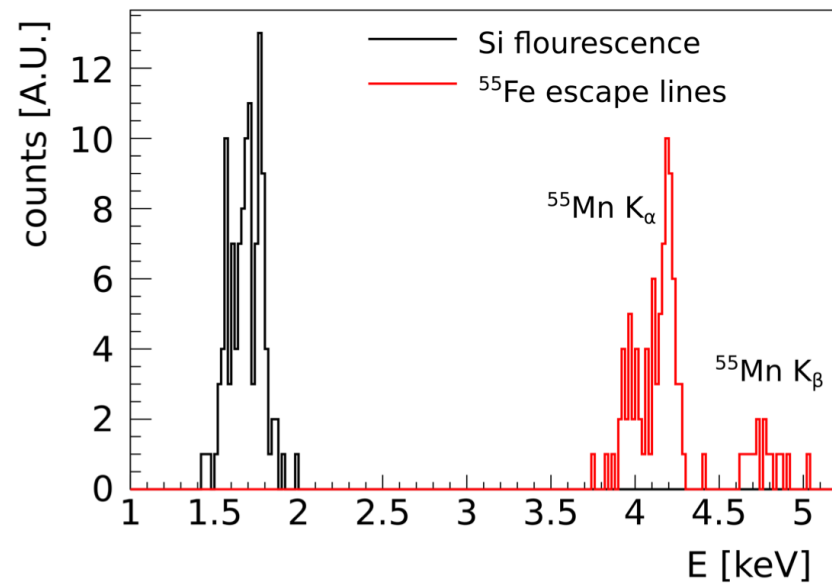
Compton
electrons
(worms) and
point like hits.



Event reconstruction



Pair of events closer than 75 μm



EC capture



10.2. Activated EC isotopes in the CCD

In September, 2013 we irradiated a DAMIC CCD with a flux of 2×10^{10} 230 MeV protons/cm² at the Warrenville proton beam facility. The instrumental performance is as expected from previous radiation tolerance measurements [16]. The aim of this irradiation was to produce uniformly distributed ⁷Be and ²²Na within the CCD bulk. These isotopes decay by electron-capture (EC) and, as the ν s and γ -rays escape the CCD, the only energy deposited is that from the refilling of the K-shell vacancy, leading to mono-energetic deposits of nominally 54 eV_{ee} and 849 eV_{ee}. A small energy shift due to the energy deposited by the recoiling nucleus following ν and γ -ray emission is also expected. Furthermore, the total activation of these isotopes can be measured precisely from the emitted γ -rays with a Ge detector. These lines will allow us to further characterize the detector for sub-keV_{ee} energy deposits in the bulk, and to demonstrate the detection efficiency of the CCD for low energy events near our threshold.

Thermal neutron calibration



10.3. Nuclear recoil energy calibration with a thermal neutron source

We are pursuing the calibration of the ionization efficiency of nuclear recoils in Si at $\sim 1 \text{ keV}_r$, crucial in understanding the energy spectrum of a potential WIMP signal in DAMIC100. The strategy is to expose a Si detector to a flux of thermal neutrons and rely on the reaction [17]:



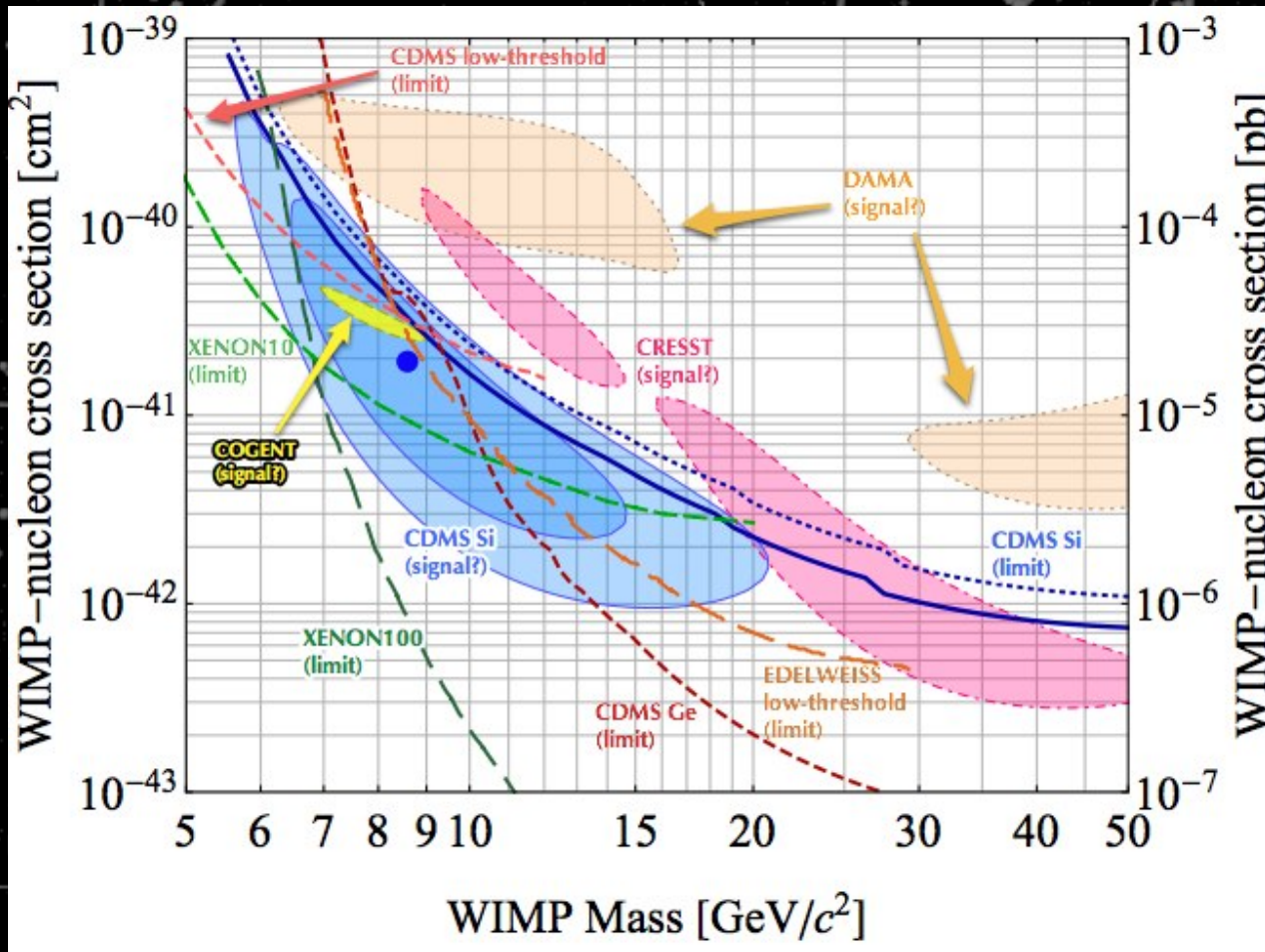
where the ${}^{A+1}\text{Si}$ nucleus recoils from the γ -ray emission due to momentum conservation. If only one γ -ray is emitted, or the lifetime of nuclear states in the γ -ray cascade is much greater than the stopping time of the recoils, then the total nuclear energy deposit is mono-energetic. Considering the maximum γ -ray energy of $\sim 10 \text{ MeV}$, these recoil lines have energies $< 2 \text{ keV}_r$. If a Si detector is exposed to a thermal neutron beam, and the coinciding γ -rays from the interaction are detected in a secondary detector, then the nuclear recoils can be effectively tagged by a time coincidence. As the recoil energy is known from the kinematics of the reaction, the nuclear recoil ionization efficiency can be measured.

As good time resolution is required to observe the coincidence, a CCD cannot be used for this calibration. We have already attempted this measurement by exposing a LAAPD [18] to a thermal neutron beam in the LENS facility at Indiana University and in a research reactor at Ohio State University, with negative results in both cases. The instrumental integrity of the LAAPD could not withstand the large neutron flux and associated backgrounds. We plan to attempt this measurement in the near future with a Si-Li detector.

Where there may be signals



- Now large collection of low mass dark matter signals (or underestimated backgrounds)
- Though mostly excluded by Xenon10 & Xenon100



- Low mass dark matter ($\sim < 10$ GeV) search region interesting
- Key is detection of low energy nuclear recoils

Ramping Up!

Better Background Predictions

- **In-situ measurement of neutrons**
- **Layer of Boron-10 on polyethylene**
- **Poly slows down neutrons - Boron captures them (2 protons & 2 neutrons) from neutron**
- **Alphas have a distinct signature**

Plasma effect in Silicon Charge Coupled Devices (CCDs)

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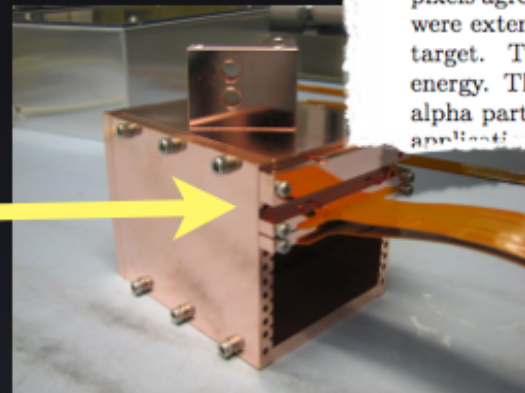
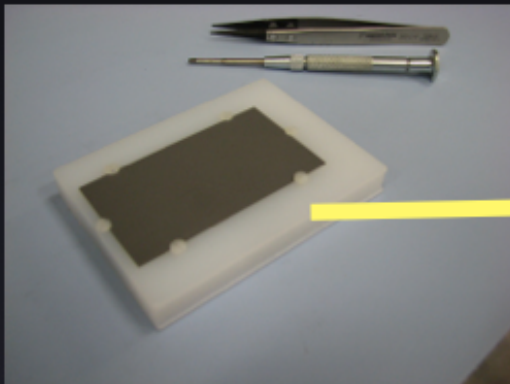
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³Centro Atómico Bariloche and Instituto Balseiro,
Comisión Nacional de Energía Atómica,
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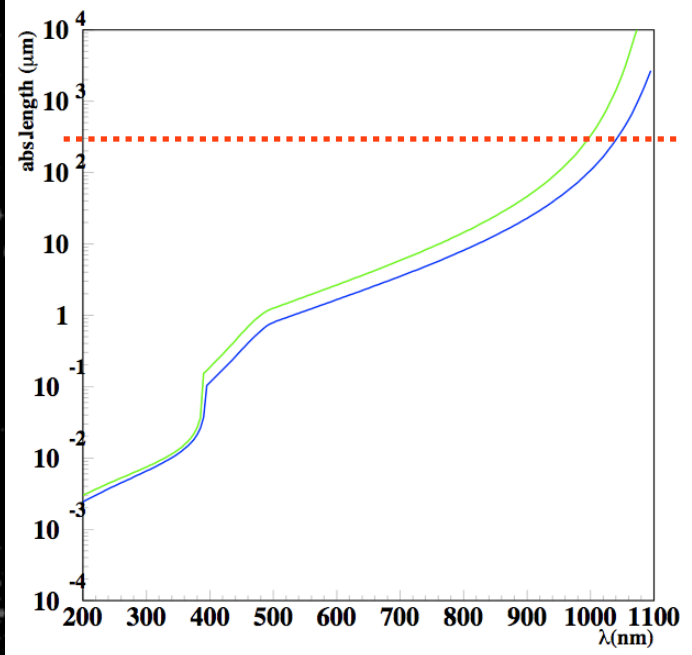
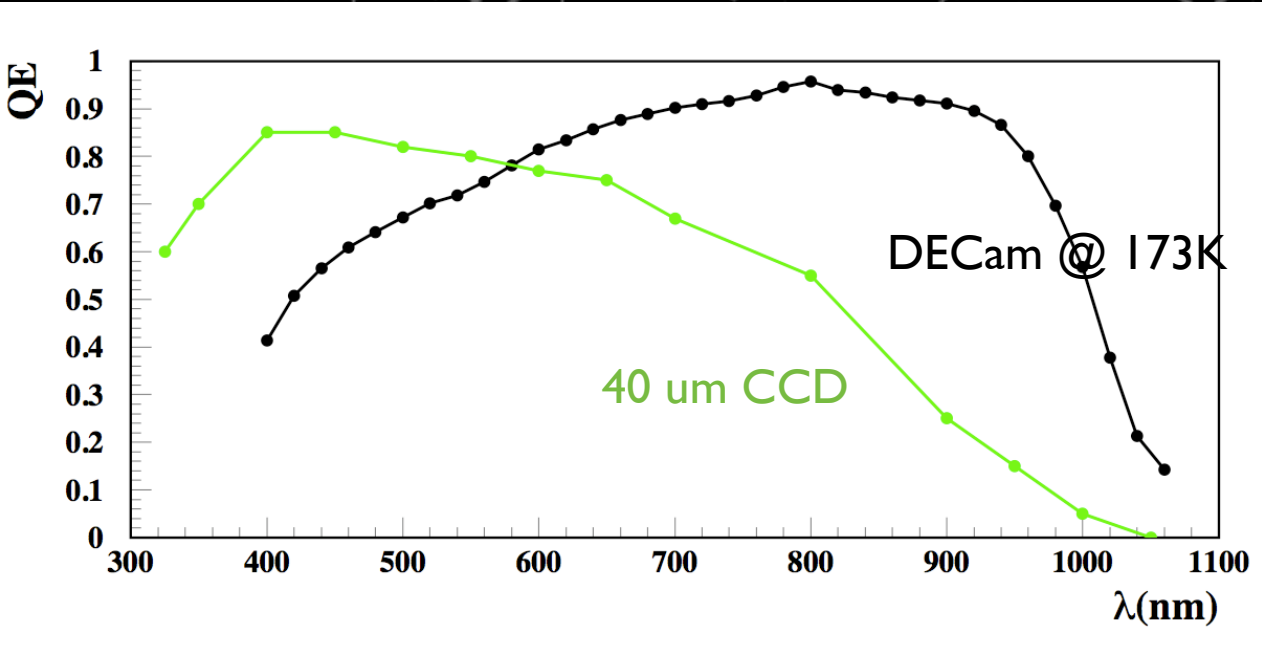
⁴Universidad Nacional del Sur, Bahía Blanca, Argentina

(Dated: May 31, 2011)

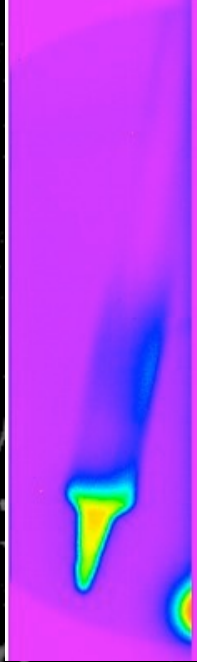
Plasma effect is observed in CCDs exposed to heavy ionizing α -particles with energies in the 0.5 - 5.5 MeV. The results obtained for the size of the charge clusters reconstructed on the pixels agrees with previous measurements in the high energy region (≥ 3.5 MeV). The measurements were extended to lower energies using α -particles produced by (n,α) reactions of neutrons in a target. The effective linear charge density for the plasma column is measured as a function of energy. The results demonstrate the potential for high position resolution in the reconstruction of alpha particles, which opens an interesting possibility for using these detectors in neutron imaging applications.



Thickness was to get IR sensitivity



250 μm thick fully depleted produces a higher efficiency in the near-IR



Soldering iron IR imaging with DECcam CCD. 20 seconds exposure with a narrow (10nm) filter centered at 810nm. (picture by K.Kuk)

Ongoing R & D



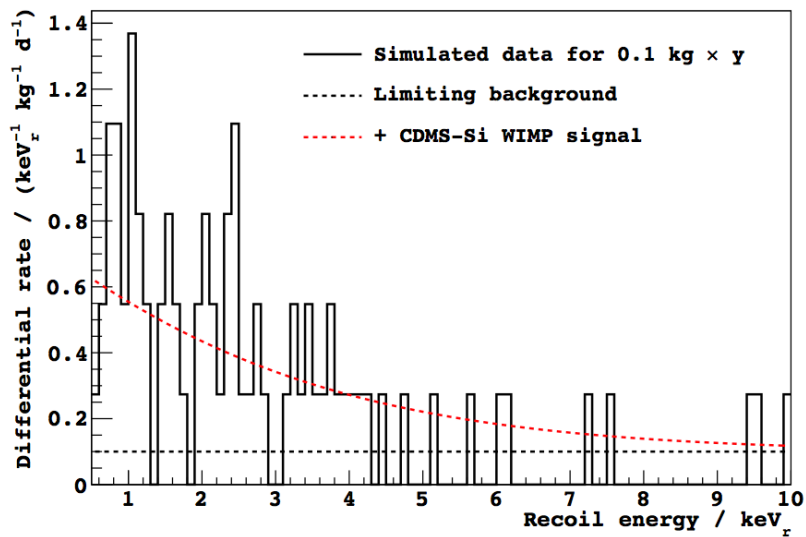
- **Neutron energy response at low energy**
 - **Electron Capture from irradiated silicon (calibration at ~ 100 eV) : could be done at PSI**
 - **Lower energy calibrations still needed**
- **Improved readout - multiple sampling (skipper) of CCD data can yield sub-eV noise**
- **CCD limitation is long exposure time : 1000s of seconds - no timing to reject triggerable backgrounds**
- **Other types of silicon detectors with fast readout and low background noise can be investigated**

Conclusions

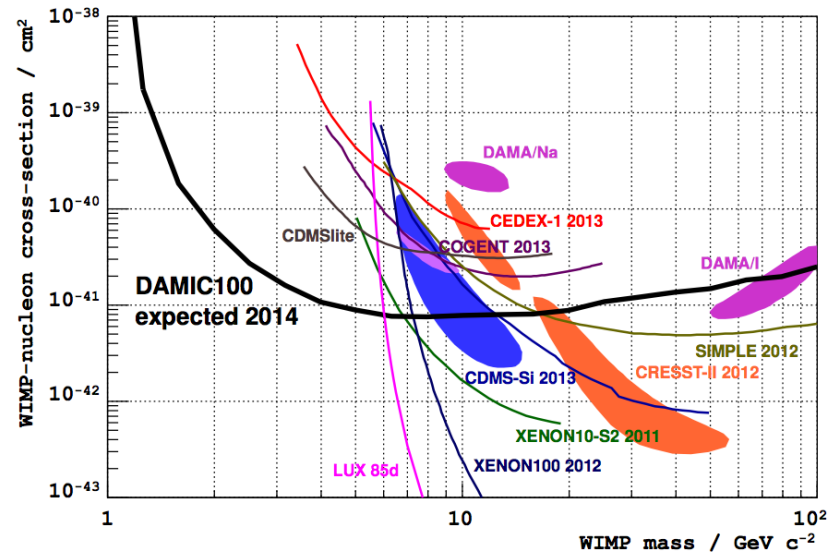


- **CCDs are a viable particle detector for low mass dark matter**
- **Can provide useful constraints on an exciting mass range for dark matter**
- **Relatively cheap (DAMIC 100 ~ 400 kCHF)**
- **Detector R&D advancing with thick, high resistivity, low noise scientific CCDs**
- **U. Zürich is playing a leading role in this experiment**
 - **Building a CCD lab for testing and calibrations**

DAMIC 2011 BACKUPS



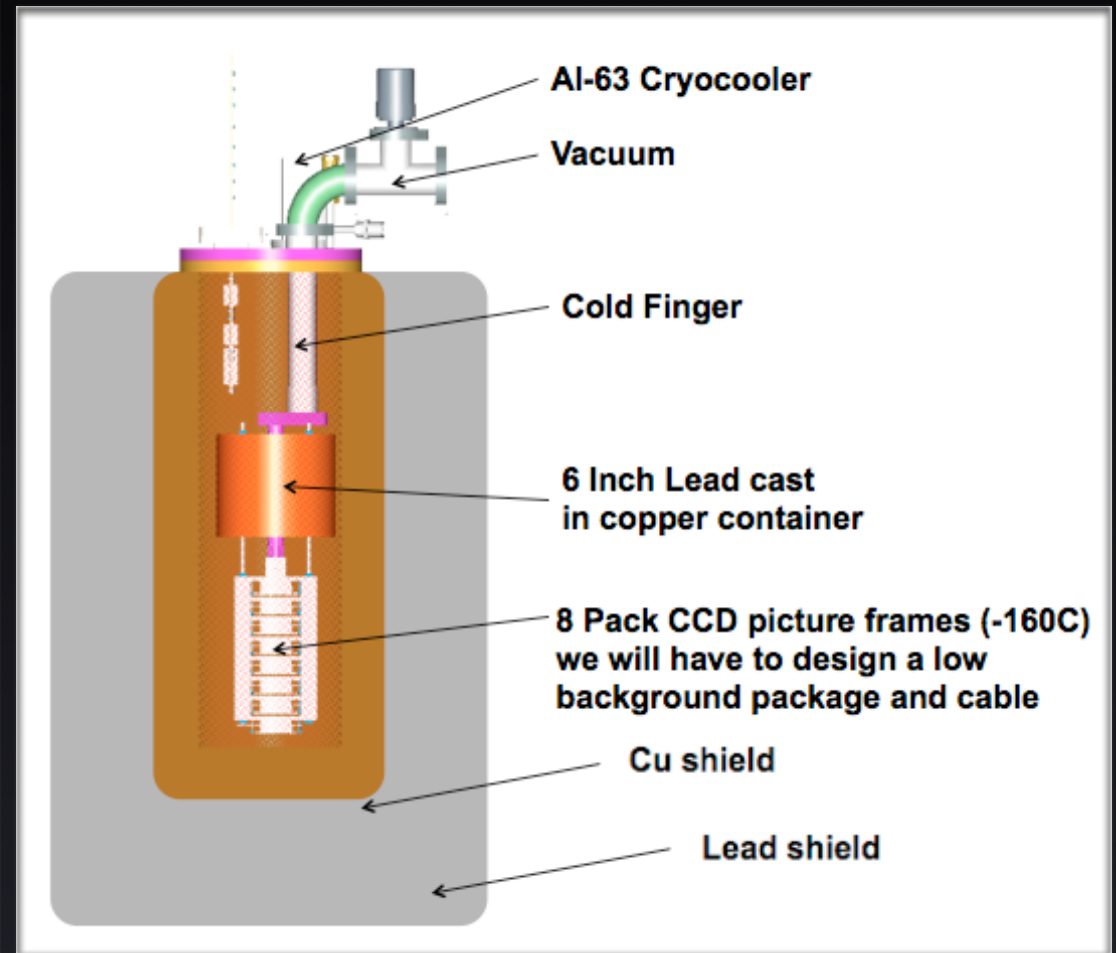
(a) Spectrum after 1 y of DAMIC100



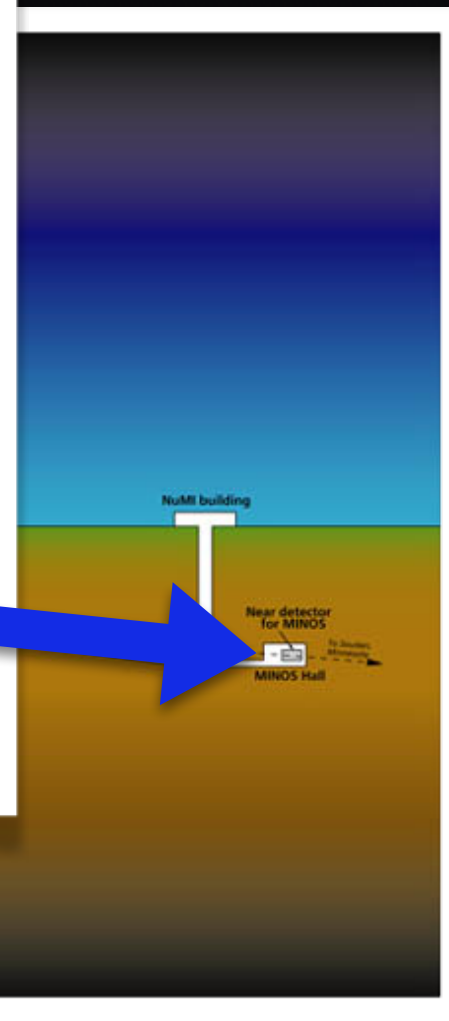
(b) Exclusion plot after 1 y of DAMIC100

Fig. 12. a) Simulated spectrum of DAMIC100, considering a WIMP with the mass and interaction cross-section of the best-fit to the CDMS-Si signal ($M_\chi=8.6 \text{ GeV}/c^2$ and $\sigma_{\chi N}=1.9 \times 10^{-41} \text{ cm}^2$) [4], standard halo parameters ($\rho_\chi=0.3 \text{ GeV}/c^2/\text{cm}^3$, $v_0=220 \text{ m/s}$, $v_E=232 \text{ m/s}$, $v_{esc}=544 \text{ m/s}$) and a $0.1 \text{ kg}\cdot\text{y}$ exposure. For this illustration, the ionization efficiency of nuclear recoils is assumed to be 0.2 and energy independent. Thus, the expected limiting background of $0.5 \text{ events}/(\text{keV}_{ee}\cdot\text{kg}\cdot\text{d})$ corresponds to $0.1 \text{ events}/(\text{keV}_r\cdot\text{kg}\cdot\text{d})$. The exponential increase at low energies, starting below 5 keV_r ($\sim 1 \text{ keV}_{ee}$), is evident. b) Under these assumptions we present a 90% exclusion plot for spin-independent interactions by performing a χ^2 test on simulated spectra with the flat background spectrum and the simulated WIMP signal for different values of M_χ and $\sigma_{\chi N}$. DAMIC100 will place the best limits on spin-independent WIMP-nucleon elastic scattering for $M_\chi < 6 \text{ GeV}/c^2$.

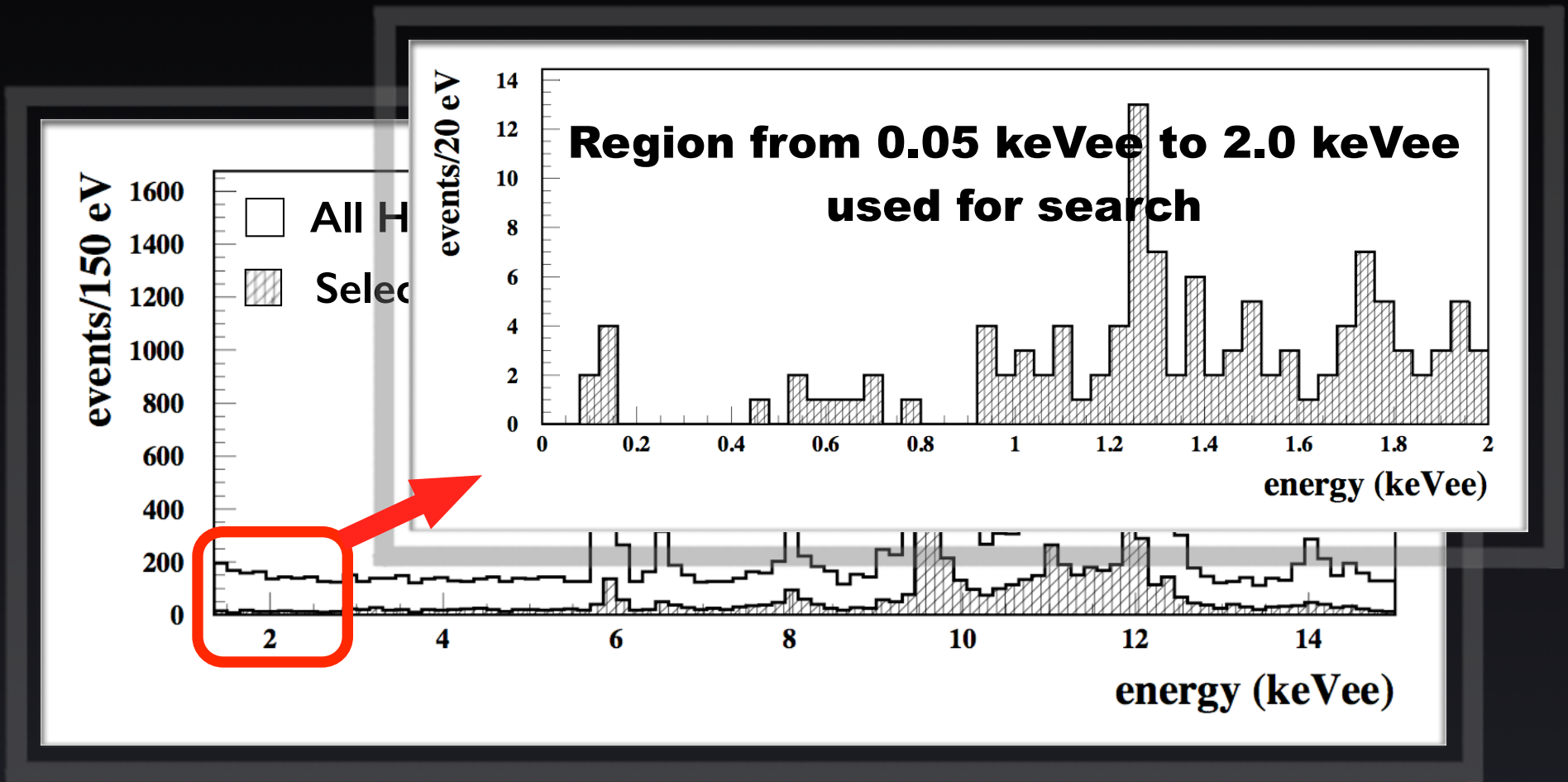
DAMIC 2011



DAMIC 2011



Energy Spectrum



Results from First Run

Direct Search for Low Mass Dark Matter Particles with CCDs

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(Dated: August 17, 2011)

A direct dark matter search is performed using fully-depleted high-resistivity CCD detectors. Due to their low electronic readout noise (RMS \sim 7 eV) these devices operate with a very low detection threshold of 40 eV, making the search for dark matter particles with low masses (\sim 5 GeV) possible. The results of an engineering run performed in a shallow underground site are presented, demonstrating the potential of this technology in the low mass region.

PACS numbers: 93.35.+d, 95.55.Aq

I. INTRODUCTION

There have been several direct-detection experiments searching for dark matter (DM) performed in recent years, and several more in development. [1]. Most of these experiments have been optimized for detecting the elastic scattering of DM particles with masses greater than 50

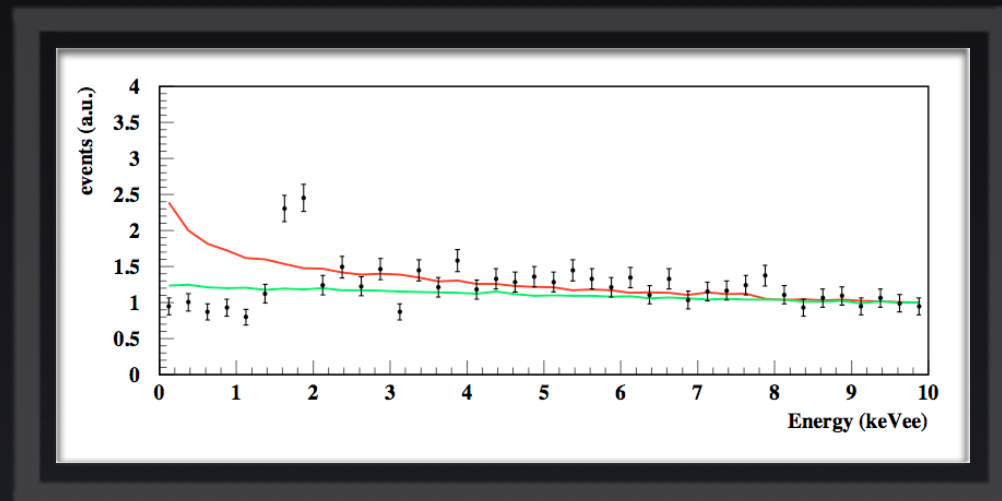
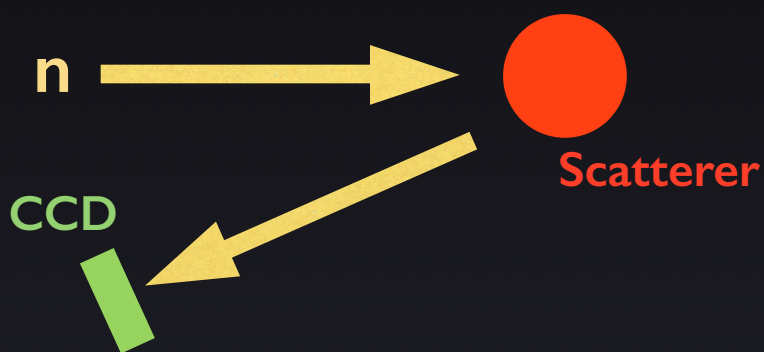
of their very low fiducial mass. The results of a search for DM using thick, fully-depleted CCDs are presented. These devices have a lower readout noise than conventional CCDs, allowing for a lower detection threshold. The results of a search for Dark Matter in GeV masses are presented. This experiment is the first DM search using this technology.

Phys. Lett. B 711 (2012) 264-269

Ramping Up!

Calibrating to Lower Energy

- **Using a mono-energetic beam of neutrons to calibrate quenching factor to very low energies**



Naturalness of Dark Matter Mass scale

1. “Wimp miracle” scale :

- Why do SUSY cross-sections provide correct relic DM density ?

$$M_{\text{DM}} \sim 100 \text{ GeV}$$

2. “Baryon-DM coincidence” scale :

- Why is the DM abundance so close to matter ?

$$\rho_{\text{DM}} \sim 5 \cdot \rho_{\text{M}}$$

- What if dark matter is more baryon-like ?
- Assume $N_{\text{DM}} \sim N_{\text{baryon}}$ in early universe

$$M_{\text{DM}} \sim 5 \text{ GeV}$$

Asymmetric DM hep-ph/1111.0293